

MEASUREMENT OF TOTAL BODY RADIOACTIVITY IN MAN

**An evaluation of detector geometries
with applications in
radiation protection and nuclear medicine**

Yngve Naversten



Lund 1982

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Fil. kand., Sm

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Techniques for the determination of whole-body radioactivity in man using uncollimated NaI(Tl) detectors have been studied. Geometrical effects and photon attenuation effects due to the different shapes of humans as well as due to varying IN-VIVO radioactivity distributions have been evaluated particularly for scanning-bed geometries and the chair geometry. Theoretically it is shown that the attenuation effects are generally dominating, for full-energy-peak pulse-range methods.

For the application in radiation protection a cheap and simple chair-geometry unit has been constructed and used at various places distantly from the home-laboratory, for studies of body activity of Cs-137 in northern Sweden. High body activities were found particularly in reindeer-breeding Lapps. The elimination rate of Cs-137 in man was studied in the stationary whole-body counter in Lund as well as with the field-system.

For the study of the performances at low and high photon energies clinical applications of methods for gastro-intestinal absorption of vitamin B12 (Co-57; 122 keV) and total body potassium determination (K-40; 1.46 MeV, K-42; 1.52 MeV) have been evaluated.

Theoretical and experimental results as well as experiences of applications in radiation protection and medicine show that the scanning-bed geometry effectively evens out redistributional effects. For optimum results, however, scatter-energy pulse-ranges rather than full-energy-peak ranges should be used.



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The following articles are included in the present thesis.
They are referred to in the text by their Roman numerals.

I: Y.Naversten:

Some Aspects of Whole-body Counting Geometries, pp. 64-87,
Proceedings of the panel CLINICAL USES OF WHOLE-BODY
COUNTING, IAEA, Vienna, 1966.

II: Y.Naversten, R.C.McCall and K.Lidén:

Semi-Portable Whole-Body Counter for
Cesium 137 and Other Gamma-Emitting Isotopes.
Acta Radiol.Ther.Phys.Biol., 1, (1963), 190-204.

III: K.Lidén and Y.Naversten:

The Enhanced Radiocaesium Levels of People
in Northern Sweden, pp 167-182, Vol. II,
Proceedings of the symposium ASSESSMENT OF RADIOACTIVITY
IN MAN, IAEA, Vienna, 1964.

IV: Y.Naversten and K.Lidén:

Half-Life Studies of Radiocaesium in Humans, pp 79-87, Vol. II,
Proceedings of the symposium ASSESSMENT OF RADIOACTIVITY
IN MAN, IAEA, Vienna, 1964.

V: Y.Naversten, K.Lidén, K.G.Ståhlberg and Å.Nordén:

The Study of ^{57}Co -Vitamin B12-absorption
Using a Whole-body Counter.
Phys.Med.Biol., 14, (1969), 441-453.

VI: Y.Naversten:

A Study of Total Body Potassium Determination
using a Whole-Body Counter.
LUNDF6/(NFRA-3032). LUMEDW/(MERI-1015)/1-16(1982).

Preliminary results in PAPER I were published as:

Y.Naversten:

A Two-Crystal Scanning-Bed Counter for Accurate
Determination of Whole-Body Activity, pp. 55-66, Vol. I,
Proceedings of ASSESSMENT OF RADIOACTIVITY
IN MAN, IAEA, Vienna, 1964.

Preliminary results in PAPER III were partly published as

Y.Naversten and K.Lidén:

High Cs-137 Body burdens of Lapps and Other People
in Northern Scandinavia and the Food Chains Involved,
pp. 517-526, Proceedings of RADIOACTIVITY IN MAN,
2nd SYMPOSIUM. Eds.: G.R.Meneely and S.M.Linde,
Charles C.Thomas. Publisher, Springfield, USA, 1965.

Preliminary results in PAPER VI were partly presented as:

K. Lidén, Y. Naversten and Lenger,V:

Total body potassium determination with a whole-body
counting technique. (In Swedish.)

Report to the Swedish Medical Research Council.

Project No.: 1396-23X-2776-01G. Lund 1970.

1. BASIC INFORMATION OF WHOLE-BODY COUNTERS

1.1. Introduction.

Primarily due to the post World War II development of the production and uses of radionuclides for industrial, medical and military purposes, it has become necessary to accurately measure the IN VIVO human content of radionuclides. So called whole-body counting techniques have therefore been developed.

A whole-body counter is an ingenious device to detect, identify and quantify the radioactivity of nuclides in human beings (Mehl, 1967; Van Dilla et al., 1967; Sorenson, 1974). The principal components are the radiation detector, the background shield and the spectrometry electronics. Particular units have been constructed for measurements in infants (Garrow, 1967; Forbes, 1968; Hukkoo et al., 1972). Other special units are constructed to measure the radioactivity in living animals (Christian et al., 1962; Van Dilla et al., 1967).

Reviews of constructional data and applications of whole-body counters are found in the literature (IAEA, 1964; IAEA, 1970). Other information is given in several proceedings of symposia devoted to radiation protection and medical applications (IAEA, 1962; IAEA, 1966; IAEA, 1972; Meneely, 1961; Meneely and Linde, 1965), and therefore only a short summary is presented here.

1.2. Systems related to activity.

Although whole-body counters can be designed for uses at any radioactivity level, most of them (IAEA, 1970) are applied to detection of low-level activity - typically 10 Bq to 10000 Bq - (Ross and Morris, Jr., 1968) or medium-level activity - typically 10 kBq to 1000 kBq - (Morris, Jr., 1965). They can also be designed for high-level activity, say 10 MBq to 1000 MBq (Morris, Jr et al. 1964). Typically large volume organic scintillation detectors are of the low-level activity type, while medium and high level systems mostly are built with inorganic scintillation detectors.

In this review, characteristic parameters and requirements of mainly low-level activity counters will be discussed. In general, similar data are needed for all types of whole-body counters regarding the response as a function of radioactivity distribution and body shape. The requirements in connection with count-rate conditions may differ, however i.e., regarding the need for a low and stable background and statistical counting precision.

1.3. Statistical aspects of detectability.

According to the general statistical laws of counting time-randomly distributed pulses (Evans 1955), the detectability is enhanced if the background count-rate is lowered. An example of definition is formula (1), where the gross count-rate obtained must deviate from the background count-rate by a certain number of standard deviations in order for a net count-rate to be regarded as detected.

$$MDA = \frac{C}{S} \left(\frac{R_b}{t_b} \right)^{1/2} \quad \text{.....(1)}$$

As is shown by Lindell, 1962, and Koeppel, 1975 we have the following relation for the statistical coefficient of variation

$$\frac{\sigma_n}{R_n} = \left[\frac{R_b}{R_n} \left(\frac{1}{t_b} + \frac{1}{t_g} \left(1 + \frac{R_n}{R_g} \right) \right) \right]^{1/2} \quad \text{.....(2a)}$$

where MDA = Minimum detectable activity, (Bq).

C = Constant dependent on the criterion of detection.

S = Sensitivity, ($s^{-1} Bq^{-1}$).

R = Count-rate, (s^{-1}).

t = Counting time, (s).

σ = Standard deviation.

$$R_n = R_g - R_b$$

$$\sigma_n = \left(\frac{R_b}{t_b} + \frac{R_g}{t_g} \right)^{1/2} \quad \text{.....(3)}$$

n, g, b are suffices for NET, GROSS and BACKGROUND, respectively.

For low-activity measurements $R_n \ll R_g$ and since R_n is proportional to the detector sensitivity, we get:

$$\frac{\sigma_n}{R_n} \propto \frac{R_b}{S} \left(\frac{1}{t_b} + \frac{1}{t_g} \right)^{1/2} \quad \text{.....(2b)}$$

From formula (2b) it is seen that for fixed counting-times, a minimum fixed statistical coefficient of variation, σ/R_n , is obtained when R_b/S is minimized, or when S^2/R_b - the figure of merit - is maximized. Systems with low and stable background are therefore needed as well as detectors with high sensitivity.

1.4. Background of shield and structural components.

The major part, about 75% or more, of the background counts in the range 0.1 MeV to 2 MeV, are in a typical low-background facility, of terrestrial origin (May and Marinelli, 1962). Low-level activity counters must therefore be constructed with carefully selected materials. The radiation detector/s must generally be located in a special room with thick

walls of materials with low concentration of radionuclides (IAEA, 1964; IAEA, 1970). In many cases, the wall material is iron, 15 to 20 cm thick, but also lead is frequently used (c.f. PAPERS II and V). Other materials of thickness with equivalent background reduction capability can be used. McCall, 1960, analyzed the criterions of the equivalence of materials of different effective atomic number. He also suggested that the activity concentration of wall materials ought to be down to about 0.4 Bq/kg. Hoforsite, an ultramafic rock, is a useful material of low activity concentration (Lindell and Reizenstein, 1964). Pure water was used by Burch and Spiers, 1953, Sievert, 1951, and Peterson et al., 1965. Other rock material has been used, e.g. chalk (Trott et al., 1965; Unnikrishnan and Cottral, 1972) and dunite (Ross and Morris, Jr., 1968). Erlenbach, 1972, and Schmier, 1972 showed that a good background reduction could be obtained at a low cost with an outer shielding of about 50 cm quartz sand and an inner shielding of about 3 cm Swedish lead. It must be in that order since Compton scattering "softens" the high energy photons, while the inner wall of high-Z material more effectively absorbs medium- and low-energy photons by the photoelectric effect. High energy photon sources, for instance activity in the building material outside the shield, even with a thick shielding, can influence the total background count-rate as is shown in PAPER II, pp. 194-195 and by Schmier, 1972.

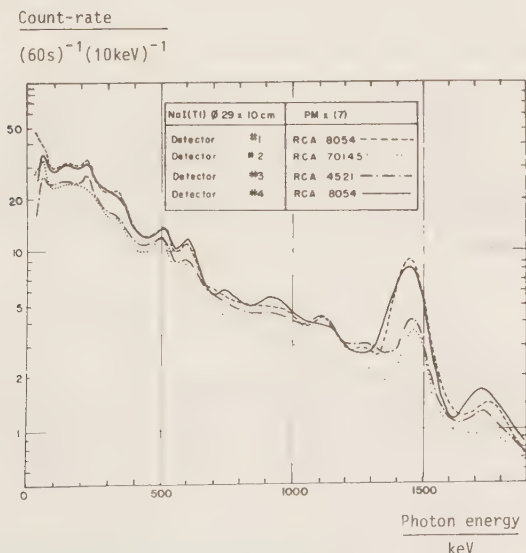


Figure 1. Background pulse-height distributions as a function of photon energy from four large identical NaI(Tl) crystals equipped with different types of photomultiplier tube assemblies. Peaks of Pb-214 and Bi-214 (c.f. TABLE I) can be identified. A peak of K-40 at 1461 keV and an annihilation peak at 511 keV are also seen.

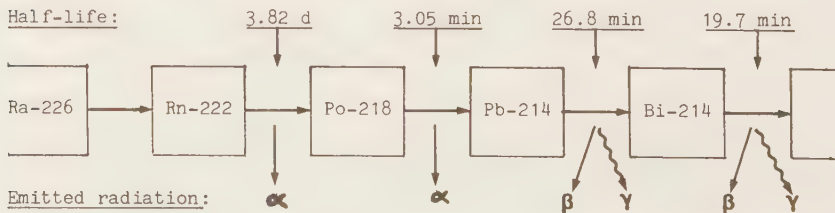
Other structural components in the chamber, detector stands and so on, must also be made of materials of low activity concentration. Of outmost importance, of course, is that the detector material itself is of high quality. For instance, NaI(Tl), photomultiplier tubes and their glass-window coupling can contain K-40, and radium and thorium daughter descendents. For potassium measurements, selected tubes can well decrease the background by a factor of about 2 (Naversten et al., 1970). See also Figure 1. As an example, this could have the result that the counting time for body potassium could be decreased from 40 minutes to 25 minutes while the statistical coefficient of variation would still be about the same (1 to 1.5 % for subjects with 100 to 150 g K).

The normal background count-rate with selected structural materials is usually reduced by factors of 50 to 100 in the most frequently used part of the energy spectrum (0.1 to 2 MeV) (c.f. Figure 5 in PAPER II). As the other parameters are constant, the above formulas, (2a) and (2b), show that detectability is then improved by a factor of up to 10.

With effective background shielding, the calibration technique is also simplified, since the amount of background photons absorbed or scattered in the subject is then small or negligible. The problems of the background depression in the higher energy ranges and the background increase below 300 keV, when the background shield is less effective, are shown in PAPER II. Other authors have indicated similar results, e.g. Rundo, 1958, and Warner and Oliver, 1966.

1.5. Background caused by radon-daughters.

For low-level activity applications, such as body potassium determinations, it is extremely important that also the background count-rate is constant, i.e. counts shall be randomly distributed around a constant mean. It should, for instance, be independent of atmospheric variations. Airborne radioactivity can cause changes, e.g., with general atmospheric alterations. Background due to radon-daughter disintegrations is an example of such airborne activity. Rn-222 disintegrates into daughter products according to the following schematic chain:



If Ra-226 disintegrates in a closed volume, an equilibrium will be established and photons with emission intensities according to TABLE I will be emitted. Due to the relatively short half-lives of Po-218, Pb-214 and Bi-214, they will be in equilibrium with their predecessor, Rn-222, within about 4 hours - that is, by that time the activity of the gaseous parent and the activities of each of its daughters will be about equal. Figure 2 shows the build-up of secular equilibrium calculated from the physical decay constants.

TABLE I
Energy and emission intensities (NCRP, 1978) of the
most frequent photons from Pb-214 and from Bi-214
in equilibrium.

Nuclide	Photon Energy keV	Emission intensity
Pb-214	241	0.07
	295	0.18
	352	0.34
	+ 12 weak intensities	0.04
Bi-214	609	0.43
	768	0.05
	934	0.03
	1120	0.14
	1238	0.06
	1378	0.03
	1402	0.01
	1408	0.02
	1509	0.02
	1764	0.15
	2204	0.05
	+ 137 weak intensities	0.24

Radon emanates from the ground and buildings into the atmosphere. Depending on how stable the atmosphere is, it will approach a certain degree of the theoretical equilibrium with its daughters. It has been shown (Moses et al., 1960; Lockhart and Patterson, 1966; Hossler, 1966, and others) that the degree of radon-daughter build-up is a function of the time of the day, the meteorological situation and the altitude. The ratio, M, may be used as an indicator for the degree of equilibrium state.

$$M = \text{Activity of Bi-214} / \text{Activity of Pb-214}$$

This ratio tends to come closer to unity at calm periods near sunset and sunrise, and as altitude increases. The degree of equilibrium certainly is very dependent on the character of the site (shape of landscape, proximity to buildings and so on). Large variations are found and mostly M-values in the range 0.2 to 0.8 are expected.

In order to obtain a low and constant background in whole-body counting facilities, special measures must be taken. In most cases this is done by adequate air-conditioning and 'absolute' air filtering. The rationale for this is the following.

The filter acts as remover of the particulate radon-daughters, while the gaseous radon is allowed to enter the low-background room. After the radon has passed the filter, its daughters will again arise. With suffi-

cient air-flow-rate, small plate-out effect and over-pressure in the chamber, this will occur outside the low-background chamber. Figure 2 shows the build-up curves of the first three radon-daughters, Po-218 (RaA), Pb-214 (RaB) and Bi-214 (RaC). Of these, only the last two emit photons of significance (TABLE I). Within five minutes, they reach only 5 % and 0.2 %, respectively, of the equilibrium level. An efficient filtering system with 12-20 air changes per hour would give a residence-time of this order. A suitable air-conditioning of the laboratory in the vicinity of the chamber may further improve the background conditions.

It is important to know that airborne radon-daughters can be deposited on surfaces, e.g., by electrostatic charges, so called plate-out effect. Parthasarathy, 1976, investigated such effects with particular reference to problems in whole-body counting. He suggested that different synthetic materials, including uncovered polythene phantoms and plastic floor and wall coverings, should be avoided within the shielded space. Deposited Bi-214 build-up may offset the advantage of air-conditioning with high flow-rate. Since especially to aerosols unattached Po-218 has a strong tendency to plate-out (Samuelsson, 1982), it motivates an air-conditioning system with some humidity controls to prevent too dry air.

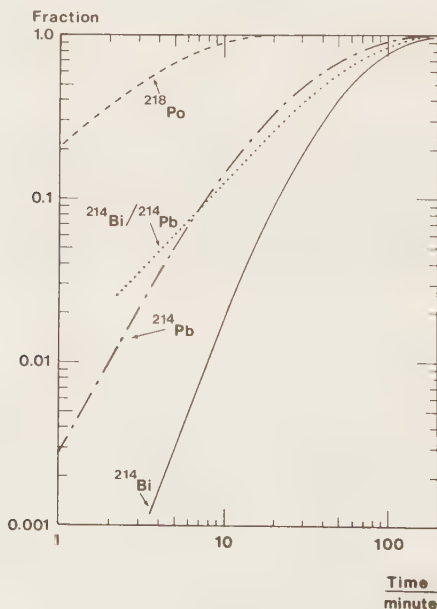


Figure 2. Fraction of equilibrium build-up of Rn-222 daughters, Po-218, Pb-214 and Bi-214, calculated from the physical decay-constants. It is assumed that at time zero there is zero concentration of the daughter nuclides.

In addition to the varying degree of secular equilibrium, the radon concentration itself varies, as mentioned, with altitude, meteorological conditions and shape of landscape. Since at certain intervals the efficiency of the filter and air-conditioning system may decrease, optimal background conditions will be obtained if the air inlet is at so high an altitude as possible. It should preferably be on the north side of the building, since down-streams along the wall will probably be most frequent on this side.

In Figure 2, the ratio Bi-214/Pb-214 is also given as a function of time. It can be used to evaluate the origin of the radon-daughter peaks in the background spectrum. Free-air conditions after passing an efficient filter system would give a ratio below 0.1, while trapped radon in the detector assembly, crystal, canning and packing material, photomultipliers, sockets, etc., tends to give peak-ratios in the range of 0.9 (Naversten et al., 1970; cf. Figure 1).

To further exemplify the magnitude of the problem, Figure 3 shows the net counts of the 1.76 MeV peak of Bi-214, obtained in one month. The average count-rate corresponds to an air concentration of about 20 Bq/m³. The maximum-minimum difference in the 1600-2000 keV range could contribute to an uncertainty of about three grams of potassium, counted in the 1300-1600 keV range. We also see that the day-time backgrounds are generally lower than the night-backgrounds. It could introduce an

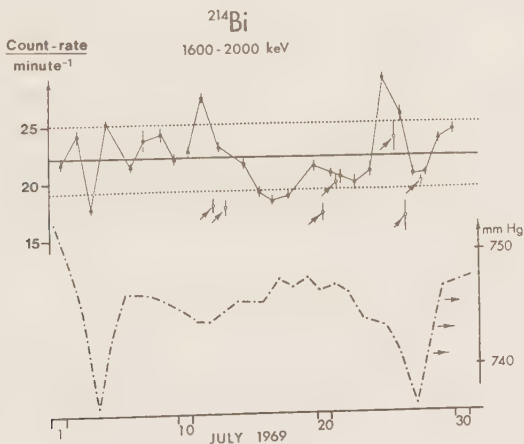


Figure 3. Net count-rate variation in the peak region of 1.76 MeV from the decay of Bi-214. Bars in each point show the counting uncertainty of one S.D. The spread as one standard deviation of night-backgrounds is indicated by the dotted lines on each side of the average-line. Day-time backgrounds are shown with open circles and arrows. The meteorological air pressure is shown at the bottom.

error of more than one g K if night backgrounds were used for day-time patient measurements. Ten times as large errors could be anticipated for a less efficiently ventilated whole-body counter, say with an "atmospheric" Bi-214/Pb-214 - ratio of about 0.6. In this particular whole-body counter (Naversten et al., 1970; c.f. Figures 1 and 6c) about 75 % of the B-214 counts were due to the detector assembly contamination. The residual part, supposedly airborne or plate-out activity, is then seen to vary well correlated with the meteorological air pressure. It should be observed that this investigation was done in Iowa City, USA, and that the same atmospheric conditions do not necessarily prevail in other areas and at anytime.

1.6. Detector sensitivity.

According to formula (2b) in Section 1.3., the sensitivity also must be as good as possible. Increasing sensitivity is sometimes more economical than decreasing background with heavy shielding. So called 'shadow-shield' counters are typical examples of this fact (Boddy et al., 1971; Dudley, 1970; Palmer et al., 1970) The requirement of high sensitivity leads to detectors with large volumes. In some of the early whole-body counters (Reines et al., 1953; Anderson et al., 1956) it was solved by the use of liquid organic scintillator contained in annular tanks large enough so that the human subject was almost completely surrounded by the detector volume. (This was also the case with the less sensitive ionisation chambers used by Sievert, 1951, and Burch and Spiers, 1953). Such systems have been called 4-pi-counters. Other liquid scintillation counters were built later (Anderson et al., 1958; Christian et al., 1962; Heinrich et al., 1965, 1966). Similar systems were also constructed with organic plastic scintillators (Delwaide, 1969, 1970). Later so called 2-pi or 3-pi-counters were developed with detector modules of plastic (Andrews et al., 1965; Tauxe and Orvis, 1966; Sköldbörn et al., 1972) or liquid blocks (Barnaby and Jasani, 1968; Smith, 1976; Smith and Cronquist, 1977) on one or several sides of the subject. These systems have exceedingly high counting efficiencies, depending on the photon energy and the pulse energy range used from for example, 10 to 80 % (Heinrich et al., 1965). In addition, the geometrical response variation is also inherently low, i.e., of good quality, with large detector volumes.

1.7. Spectral resolution of organic scintillation detectors.

The main draw-back of these types of systems is their rather poor spectral resolution due to the low effective atomic number. (See Figure 4). For instance, trimethylbenzene (Faissner et al., 1963) has an effective atomic number of about 5.6, and a density of about 1000 kg/m³. It is therefore difficult to resolve peaks, even with photon energy differences in the range of hundreds of keV. In regard to nuclide identification, organic scintillator detectors are therefore not so well suited for applications in radiation protection.

Although organic scintillator whole-body counters are important for applications in both radiation protection and medicine, they will not be discussed in detail in this review since their construction and counting conditions are distinctly different. The main object is instead to evaluate the performance of some NaI(Tl) detector systems.

1.8. Spectral information from NaI(Tl) scintillation detectors.

The NaI(Tl) crystal has a rather high effective atomic number, about 50, and a rather high density, 3670 kg/m^3 . The probability of total absorption of photons is therefore rather good in reasonably small detector volumes. Whole-body counters with NaI(Tl) scintillation detectors are suitable particularly when identification of several radionuclides in the human body is desired. The relatively good spectral resolution for NaI(Tl) crystals, in comparison with large organic scintillation detectors, is illustrated in Figure 4. (Cederquist and Naversten, 1967).

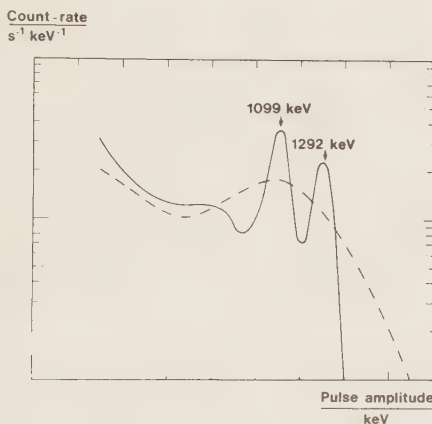


Figure 4. Typical pulse-height distributions of Fe-59 in man.

————— with NaI(Tl) scintillation detector.

----- with large organic scintillation detector.

The comparatively good spectral resolution of NaI(Tl)-systems makes it possible to use the shape of pulse-height distribution to obtain additional information on activity depth and distribution in the human body. This was already pointed out by Rundo in 1958. This effect is further studied in this thesis in PAPERS I, V and VI.

Information is presented in PAPER I, TABLE I on the counting response for three radionuclides in different locations. Analysis of the pulse-amplitude distributions shows that they differ greatly, depending on the body activity distribution. This is exemplified in Figures 5a, 5b and 5c and in TABLE II. These data illustrate that the use of counts in the scattered photon energy regions potentially can give whole-body counting results that are less dependent on the activity distribution. Since photons of deeply located sources have higher probability to interact with matter, such sources will give larger count-rate contributions in the scatter energy region of the spectra, as shown in Figure 5. Due to the multiple-scattering in large volumes, such as humans, a large con-

tribution of low-energy photons, down to about 100 keV, is created. Thus also for high-energy photons, above 500 keV, count-rate distributions down to at least 100 keV must be considered. In this way minimal fictitious attenuation coefficients will be in effect. As shown in PAPER I, the counting technique will then have minimal dependence on the activity distribution in the body. It should be pointed out that a wide energy span does not necessarily improve the statistical counting-precision. Since the wide energy range includes the main photon energies of radon-daughters, it may also introduce extra problems if the airborne activity varies.

TABLE II

Ratio of integral count-rate above 100 keV to count-rate in the full-energy-peak region, for two photon energies, 364 keV of I-131 and 668 keV of Cs-132, with activity in different organs of a plastic manikin (ALDERSON).

The figures are averaged values for single-detector scanning-bed geometry and for chair geometry with one NaI(Tl) crystal; diameter: 12.5 cm, thickness: 10 cm.

Source distrib- ution	I-131 100 - 400 keV 325 - 400 keV	Cs-132 100 - 725 keV 600 - 725 keV
Point, 50 cm	1.6	1.9
Thyroid	2.8	3.1
Whole-body	3.3	3.9
Liver	3.6	3.8
Bladder	4.4	4.7

1.9. Types of NaI(Tl) whole body counting systems.

Due to manufacturing difficulties and high cost, most NaI(Tl) systems up to now only cover a small part of the body. Single or few-detector systems have normally been used. As reviewed in PAPER I, the main categories are recognized as:

- * The arc-geometry.
- * The chair geometry.
- * The bed geometry with an array of fixed detectors.
- * The scanning bed geometry with one or several detectors moved along the human subject.

Single or multiple NaI(Tl) detector systems typically have efficiencies below one per cent. As an illustration, the point-source full-energy-peak efficiency (detected fraction of emitted photons) of a commonly used detector size as used at our laboratory (McCall and Lidén 1962) is given in TABLE III. It is based on the Monte Carlo calculations by Miller and Snow, 1957, 1960. The full energy peak fraction for detectors of the sizes normally used varies from about 0.4 up to 1.0. For distributed large sources, the use of also scattered photons normally enhances the efficiency by a factor of three to six for photon energies up to about 1.5 MeV. See TABLE II. Detector dimensions up to about 30 cm (diam.) by 10 cm (thick) are becoming more frequent. The efficiency is then higher in relation to the increased solid angle and improved physical photon interaction characteristic, with higher peak to total ratio.

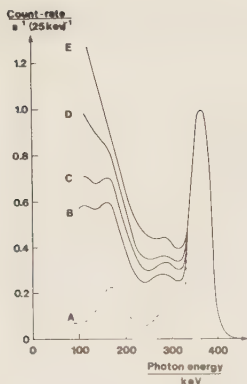


Figure 5a.

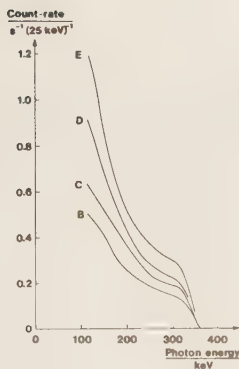


Figure 5b.

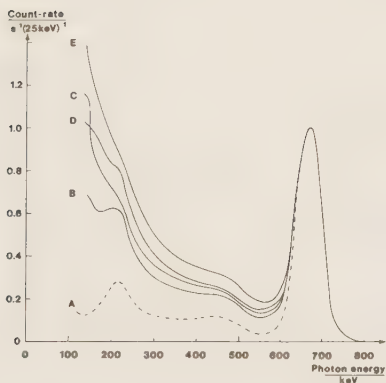


Figure 5c.

Figure 5. Pulse-height distributions of two radionuclides in different organs of a human-like phantom (ALDERSON*) and a point source at 50 cm. The pulse-height distributions from activity in the organs were obtained with one scanning detector in front of the phantom.

A: Point source. B: Thyroid. C: Whole-body. D: Liver. E: Bladder.

- Of I-131 mainly 364 keV photons, contribution from 637 keV photons is stripped off using the 668 keV photons of Cs-132.
- Distribution of scattered photons from 364 keV primary energy. The main primary distribution is stripped off by the use of the pulse height-distribution of the point source.
- Of Cs-132 with primary photon energy 668 keV.

* REMAB/REMCAL phantom from:
Alderson Research Laboratories, Inc.
Springdale, Connecticut, USA.

TABLE III

APPROXIMATE FULL-ENERGY-PEAK EFFICIENCY FOR NaI(Tl), 12.5 cm DIAM.x10 cm THICK FOR THREE PHOTON ENERGIES (Point source in air on detector axis)			
Distance	320 keV	660 keV	1460 keV
20 cm	17.6×10^{-3}	12.0×10^{-3}	7.1×10^{-3}
50 cm	3.3×10^{-3}	2.3×10^{-3}	1.4×10^{-3}
80 cm	1.3×10^{-3}	1.0×10^{-3}	0.6×10^{-3}

Single or few-detector systems with fixed position in relation to the human body generally have highly inferior geometric characteristics in comparison with large volume organic scintillator systems. This means that the count response of activity in the body may vary significantly with body shape and internal activity location and translocation (Miller and Marinelli, 1955; Rundo, 1958; Cederquist and Lidén, 1962; Chhabra, 1964; 1968; Naversten, 1964).

As reviewed in PAPER I, different multi-detector systems have been developed in order to further improve the stability of the response. In this category of systems, the one reported by Ross and Morris, Jr., (1968) is one of the more elaborate whole-body counters. A further specialized system with 54 fixed detectors is described by Cohn et al., 1969. Extraordinary detector volumes are also obtained with crystal sizes up to about 30 cm diam. x 10 cm thick. See Figure 6c. With such large detectors the spectral peak/total ratio is also markedly increased and full-energy peak efficiencies of high energy photons (e.g. 1.46 MeV of K-40) of about 2% are obtained (Naversten et al., 1970).

Other multi-position detector systems (c.f. Figure 8 in PAPER I and Miller, 1962, 1964, Hukkoo and Miller, 1964; Burkinshaw et al., 1972) or scanning detector/s as shown in Figure 6a (Naversten, 1964), Figure 6b as used in studies for PAPER V and VI, and Figure 6c (Naversten et al., 1970) have been built to simulate the geometric characteristics of large volume organic scintillator systems. With the patient reclining on a bed, these systems have the possibility to also transfer some information on the activity location in the body (Miller 1964a, 1964b, 1964c; Bass et al., 1970; Parr et al., 1972; Price et al., 1972; Watts et al., 1972; Schober et al., 1978).

The bed geometries have some definite advantages, such as

- * The subject can recline comfortably and relaxed with minimal movements of the body during the counting period.
- * Due to the rather constant longitudinal response, the calibration technique is simplified.
- * Potential possibilities exist to simultaneously get a rough assessment of the longitudinal activity distribution within the body.

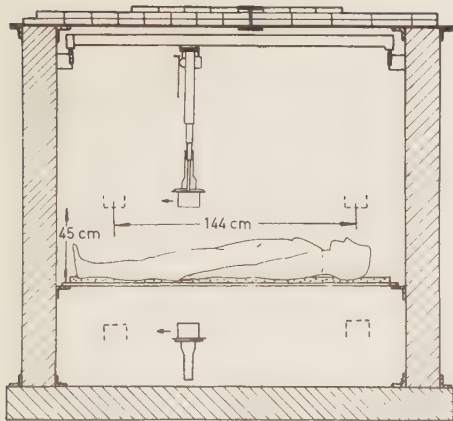


Figure 6a. Iron-room counter. Background shield, 18 cm laminated iron sheets and 3 mm lead (SN 3.1., IAEA 1970). Scanning-bed geometry with two NaI(Tl) crystals, diam.: 12.5 cm; thickness: 10 cm, movable on each side of the patient. Scan-length: 144 cm. Distance between crystal faces: 70 cm.

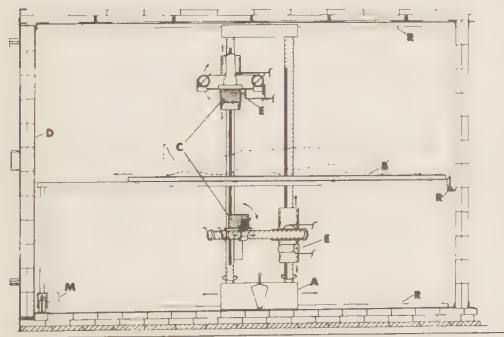


Figure 6b. Lead-room counter. Background shield, 8 cm lead. (SN 3.3., IAEA 1970). Scanning-bed geometry with two freely adjustable NaI(Tl) crystals; Diam.: 12.5 cm; thickness: 10 cm; movable on each side of the patient. A: Motor and gear for longitudinal movement. B: Longitudinally and transversally movable patient table. C: NaI(Tl) crystals. D: Door of the lead-room. E: Detector positioning stand and forks. M: Motor for table movement. R: Rails for stand and table movement.

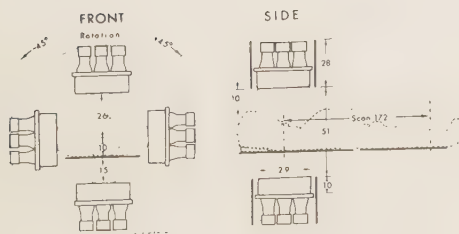


Figure 6c. Iowa City rota-scan counter (Naversten et al., 1970). Scanning-bed geometry with four NaI(Tl) crystals; diam.: 29 cm; thickness: 10 cm; 10 cm radially adjustable and can be rotated $\pm 45^\circ$ during the scan movement, which is 172 cm.

It is worth while to point out that the very first type of whole-body counter, the arc-geometry (Evans, 1937), also shows the feature of constant longitudinal response, although the efficiency is very low and the posture uncomfortable.

Several systems of "shadow-shield" type (Bader and Lorenz, 1977; Boddy et al., 1971; Dudley, 1970; Marx et al., 1980; Palmer et al., 1970) take advantage of the superior qualities of the scanning-bed principle which is of great value for clinical applications in particular.

2. PROPERTIES OF SCANNING WHOLE-BODY COUNTERS

2.1. Introduction.

The main purpose of the investigation presented in PAPER I, SOME ASPECTS OF WHOLE-BODY COUNTING GEOMETRIES, is to clarify the geometrical performance and the extent of source self-attenuation with NaI(Tl) detector systems, especially those with uncollimated scanning detectors. A general survey of the counting properties of systems with NaI(Tl) scintillation detectors can be deduced from a series of simplified situations.

Literature on the research developments until 1965 is reviewed in the first section of PAPER I. The last section contains definitions and calculations of different parameters involved in whole-body counting. A complementary review of literature, as well as some further illustrations of parameters and calculations, are given in this thesis.

Several other authors have referred to this investigation and the preceding report (Naversten, 1964). Valuable studies of scanning system characterization have been done by Hamann, 1977. His work is mainly based on the original investigation done by the present author (Naversten 1964, Naversten 1966). Hamann made extensive analytical evaluation of the geometrical dependence by computer calculations for different scanning configurations with constant and varying detector speed. Similar work with constant speed was done by Morsy et al., 1976, for a coarsely collimated four-detector system. Before that, Mehl, 1966, 1967, had summarized the counting performance of line sources for NaI(Tl) scintillation detector systems. A part of the present thesis also involves such idealized situations, applied to scanning geometries. This idealization of the problem of counting internal activity in humans may be valuable when one wishes to estimate or consider different counting methods (c.f. section 2.6.). Ben Haim and Dudley, 1966, and Dudley and ben Haim, 1968, made investigations similar to the present one regarding the counting response variation in phantoms and on human subjects by the use of full-energy-peak pulses, as well as with pulses of scattered photons. With special reference to the attenuation problems, Genna (1966) and Sorenson (1974) extended Evans geometric mean concept of the arc-geometry (1937) to be applicable particularly to the scanning-bed geometry. Andrasi and Koetel, 1973, 1975, have used a computer method to calculate the full-energy peak efficiency for a chair and a scanning bed geometry for different photon energies and different radionuclides in a human-like phantom. The results of the calculations agreed well with results of experimental measurements. Similar work was done by Julius and Verhoef, 1972, for a multi-detector-array system and by Mariss et al., 1978, for a six-detector scanning-bed system.

Although, as summarized above, many investigations have been done of the vast problem of accurate assessment of radioactivity in the human body, with its various sizes and shapes, further systematical studies are warranted. In the following sections, a detailed description of the principles of the whole-body counting scanning-bed technique is presented.

2.2. Fixed detector - point source geometry.

Figure 7 illustrates the measuring geometry of a fixed position detector counting a point source of certain mono-energetic photons at a certain distance on the central axis of the detector. Under certain restrictions it can be generalized to other source-detector directions, (Ψ).

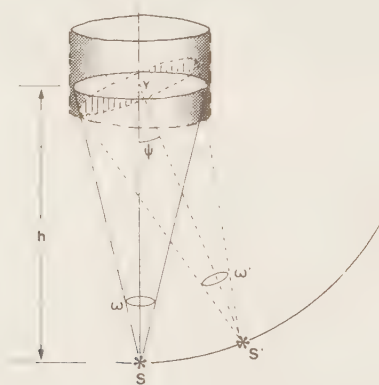


Figure 7. Fixed detector - point source on the central axis, S, and off-axis, S', at angle Ψ and ω' are solid angles of Y, as seen from the source positions.

In this and the following section, a simplified formulation is given where a source of activity, A (Bq), with photon emission intensities, q, with mono-energetic energy, E (keV), in all cases is measured in a total counting time, t (s).

Referring to PAPER I, we separate the intrinsic efficiency, IE, and the geometrical factor, GF. Of course, if the point source is in an absorbing medium, an attenuation factor must also be applied. In this summary, IE is called ϵ and, for simplicity, the GF is compared with a target area, called Y (See Figure 7). Both factors are normally dependent on the photon energy, E, the angle, Ψ , and the distance, h. For selected shapes of detectors and restricted ranges of h and Ψ , the product $\epsilon(h, \Psi) \cdot Y(h, \Psi)$ can be nearly (or sufficiently) constant (c.f. Figure 8 in this thesis and Figure 8b in PAPER I). Formula (4), given below, can be applied to such geometries as arc-, chair- and bed-geometries with one or several fixed detectors.

h: Effective detector-source-distance, (cm).

Y: Effective detector target area, (cm^2), as seen from the source.

ϵ : Detector efficiency.

N_p : Detector response for point source.

$$N_p = A \cdot q \cdot \epsilon(h, \Psi) \cdot \frac{Y(h, \Psi)}{4\pi h^2} \cdot t \quad \dots (4)$$

2.3. Scanning detector - point source geometry.

It is assumed that the detector is being moved at a constant speed along a linear orbit at a distance, h , from a point source, as illustrated in Figure 9. Analogously with definitions above, we have the following quantities:

h : Effective distance, (cm), source-detector orbit.

a : Half length, (cm), of scanning orbit.

c : Source distance, (cm), from axis of symmetry.

u : Momentary detector distance, (cm), from axis of symmetry;
 $u > 0$ if the detector is on the same side of the perpendicular plane of symmetry as c .

v : Scanning speed, ($\text{cm} \cdot \text{s}^{-1}$).

$Y(c, u)$: Momentary effective detector area, (cm^2), in source-detector direction.

$\epsilon(c, u)$: Momentary detector efficiency in source-detector direction.

N_{ps} : Response of point source for a whole scan with one detector.

$$N_{ps} = \int_{-a}^a A \cdot q \cdot \epsilon(c, u) \cdot \frac{Y(c, u)}{4\pi(h^2 + (c-u)^2)} \cdot dt; \quad dt = \frac{du}{v} = \frac{t \cdot du}{2a} \quad \dots (5a)$$

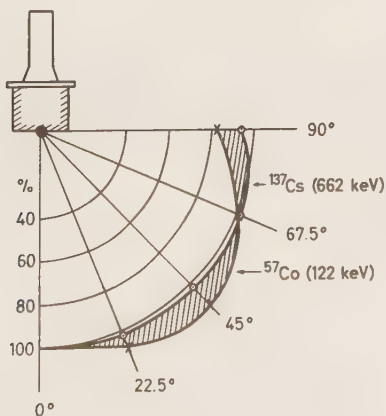


Figure 8. Angular count-rate dependence measured with a NaI(Tl) scintillation detector; diameter: 12.5 cm; thickness: 10 cm; for point sources of Co-57 and Cs-137 at a distance of 100 cm from the centre of the face of the crystal.

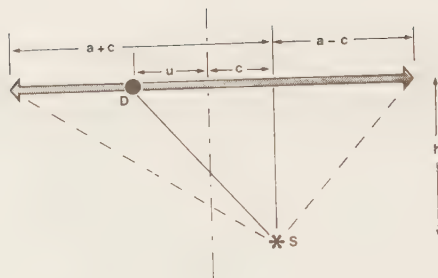


Figure 9a.

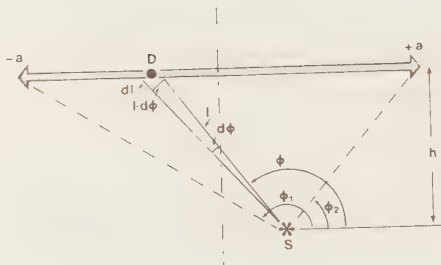


Figure 9b.

Figure 9. Scanning detector - point source geometry. Detector orbit, length $2a$, is indicated by double arrow, D is the detector, u its coordinate and c and h are coordinates of the source, S. In polar representation, l and ϕ are relative coordinates of D and S.

a) Cartesian coordinates. b) Polar coordinates.

In formula (5a) $\epsilon(c,u)$ and $Y(c,u)$ are both usually functions of c and u , the coordinates of source and detector. For selected shapes of NaI(Tl) detectors, however, the product $\epsilon(c,u) \cdot Y(c,u)$ can be nearly constant, as shown in Figure 8. Such a case can also be exemplified by scanning a cylindrical NaI(Tl) detector with its axis lying horizontally perpendicular to the long axis of the human subject (c.f. Hukko and Miller, 1964; Miller 1964b). If $\epsilon \cdot Y$ is assumed constant, we then get

$$N_{ps} = A \cdot q \cdot \epsilon(c,u) \cdot Y(c,u) \cdot \frac{t}{8\pi a} \cdot \int_{-a}^a \frac{du}{h^2 + (c-u)^2} \quad \dots (5b)$$

or

$$N_{ps} = A \cdot q \cdot \epsilon(c,u) \cdot Y(c,u) \cdot \frac{t}{8\pi a h} \cdot \left[\arctg \frac{a+c}{h} + \arctg \frac{a-c}{h} \right] \quad \dots (5c)$$

From formula (5c) we see that the response is proportional to the angle of view of the scanning orbit as seen from the point source. This can be seen directly if the response is derived from the polar coordinates.

$$N_{ps} = A \cdot q \cdot \varepsilon(c, u) \cdot Y(c, u) \cdot \int \frac{dt}{4\pi l^2}; \quad \dots (5d)$$

$$dt = \frac{t \cdot du}{2a}; \quad du = \frac{ld\Phi}{\sin\Phi}; \quad h = l \cdot \sin\Phi$$

We then obtain

$$\int \frac{dt}{4\pi l^2} = \frac{t}{8\pi a \cdot h} \int \frac{d\Phi}{\Phi}$$

and then

$$N_{ps} = A \cdot q \cdot \varepsilon(c, u) \cdot Y(c, u) \cdot \frac{t}{8\pi ah} \cdot (\Phi_1 - \Phi_2) \quad \dots (5e)$$

Relating N_{ps} to the emitted number of photons, we obtain the geometrical efficiency, $E(\text{point})$, of the total scan, as $G(\text{eff})$ is defined in PAPER I:

$$E(\text{point}) = \frac{N_{ps}}{A \cdot q \cdot t} \quad \dots (6)$$

By analogy and reciprocity-approach, similar formulas also are valid for the reverse situation with a fixed detector and a line-source.

2.4. Scanning detector - line source geometry.

The formula for a point source can be integrated to a line source of length, L , with constant activity, $dA=A/L$, along the source. (See Figure 10). If z is the coordinate of the line increment, dz , we get the efficiency, $E(\text{line})$, of a line source and one scanning detector by integration of formula (5c) or (5e):

$$E(\text{line}) = \frac{\varepsilon(z, u) \cdot Y(z, u)}{8\pi aL} \cdot \left[a_1 \cdot \text{arctg}(a_1) \cdot a_2 \cdot \text{arctg}(a_2) \cdot a_3 \cdot \text{arctg}(a_3) \cdot a_4 \cdot \text{arctg}(a_4) - \ln \left(\frac{(1+a_1^2)(1+a_4^2)}{(1+a_2^2)(1+a_3^2)} \right)^{1/2} \right] \quad \dots (7)$$

$$\text{where } a_1 = \frac{a+c+L}{h}; \quad a_2 = \frac{a-c-L}{h}; \quad a_3 = \frac{a+c}{h}; \quad a_4 = \frac{a-c}{h}$$

In formula (7) c is the distance from the closest end of the line source to the plane perpendicularly through the centre of the scanning orbit, plane of symmetry; $c>0$ if the whole line is at only one side of the centre plane and $c<0$ if it is extended on both sides of the centre plane; as before $u>0$ if the detector is at the side where $c>0$.

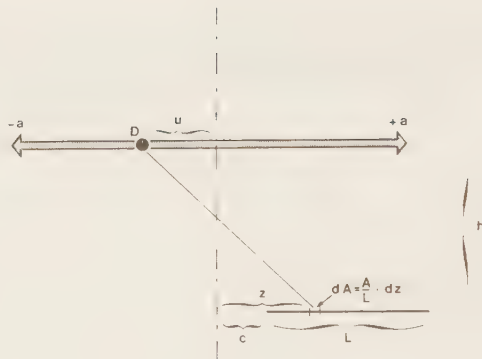


Figure 10. Scanning detector - line source geometry. Detector orbit, length $2a$, is indicated by the double arrow, D is the detector, u its coordinate, c and z are coordinates and L the length of line as explained in the text.

2.5. Scanning detector - volume source geometry.

For a more accurate picture of the characteristics of the detector systems the formulas may be further extended to volume sources of different simple shapes such as parallelepipeds, circular and ellipsoidal cylinders. This extension is particularly important in order to study the often so dominant effects of self-attenuation of the photons on the system efficiency.

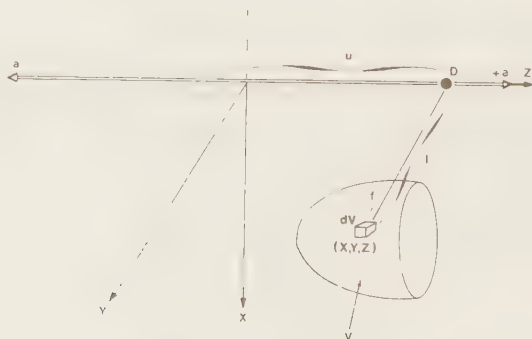


Figure 11. Scanning detector - volume source geometry. Detector orbit, length $2a$, is indicated by the double arrow, D is the detector, u its coordinate, x , y and z are coordinates of the volume increment, dV , and f the attenuation path length within the volume, V .

Given the scan-length, $2a$, and integration over the volume, V , with the presently given definitions (see Figure 11), the formula (5) given in PAPER I, will be as in formula (8) in this thesis. Here $\Sigma(\text{vol})$ represents the system efficiency for a volume source with attenuation.

$$\Sigma(\text{vol}) = \int \int_{V-a}^{+a} \frac{\epsilon(x,y,t,u) \cdot Y(x,y,z,u) \cdot e^{-\mu \cdot f(x,y,z,u)}}{dA \cdot dt} \quad \dots (8)$$

where $dt = \frac{t}{2a} du$; $dA = \frac{A}{V} dV$

where ϵ , Y and f are factors pertaining to the momentary location of the detector, u , and the location of the volume increment, (x,y,z) . In order to use this formula for body activity assessment, the factors ϵ and Y , individually or their product, have to be measured and if they are not angularly invariant, their dependence has to be taken into consideration at the integration.

2.6. Discussion of different scanning geometries.

In this thesis it is intended to show details of response variations and to give a method for estimating how efficiencies vary for different geometries. It is done with the assumption of detector isotropy. It is not intended to give a method for accurately calculating the absolute whole-body counting efficiency. The formulation can be used to acquire such data, however, if supported by accurate experimental results of attenuation coefficients and of the angular dependence of the individual detectors involved. Information of this type is occasionally found in the literature (Andrasi and Kötel, 1973, 1975; Julius and Verhoef, 1972). In the contexts of detector isotropy, the parameters ϵ and Y can be canceled out by reference to a "measurement" of a source at a standard position. A distance of one meter is chosen here. This is appropriate since we then get estimates of different whole-body counting geometries in relation to the well-known one-meter-arc geometry. In such examples, it is assumed that the total counting time and the total source activity are held constant. In most cases calculations are done under the assumption that the 'subject' is 20 cm thick and for illustration of transversal variations an elliptical cross-section with diameters of 20 cm and 40 cm is utilized.

In PAPER I, the analysis is mainly based on point sources. The purpose is to first show simple basic data from which integration can be done to volumes of different sizes and locations. The spatial response variations expected due to geometry parameters ($\mu=0$), and due to attenuation parameters, ($\mu>0$), are studied. The magnitude of distortions resulting from geometry and attenuation are given separately. It is especially done regarding the longitudinal and the vertical directions. It is further illustrated in this thesis, also in the lateral direction, for single and double detector geometries, Figures 13. Here, in all cases, the distance, h , is the same, while scan-length, $2a$, and attenuation, μ , are varied, as shown in Figure 12. The longitudinal variation, i.e. in the sagittal plane, and the transversal variation are calculated for an elliptical cylinder, length 200 cm, width 40 cm, thickness 20 cm, with

assumed constant activity concentration. In the Figures 13 isocontours are given at 5 % intervals. They are normalized to 100 % at the surface of the volume. In the sagittal plane it is normalized at the centre plane. The transversal contours (half section) are individually normalized to the surface point at their own longitudinal position. For comparison, corresponding results of one-meter-arc geometry are also given in Figure 14. As is shown in PAPER I, the different scan-lengths differ most significantly towards the scan-ends.

The attenuation is a very decisive effect for the absolute efficiency in counting the whole body and its regional body activity, i.e. redistributional effects. The relative behavior of the response for a certain geometry is, however, approximately the same for quite different attenuation coefficients. This is demonstrated for point sources in Figure 19 of PAPER I. This relative independence of μ is of course even more apparent when considering volume sources. For the study of geometrical parameters, calculations can therefore usually be done with sufficient accuracy without the more complicated corrections for attenuation. Such estimations may generally introduce errors of less than 10%.

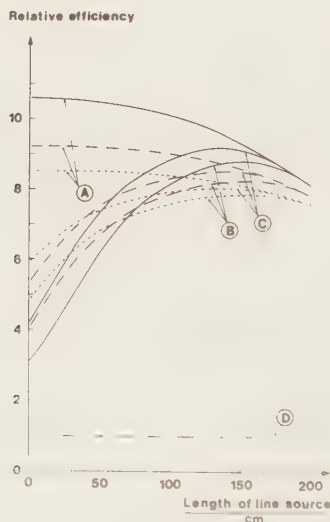


Figure 15. Relative counting efficiency of line sources as a function of source-length, for double-detector scan-geometry. Source-orbit-distance: 30 cm.

Scan-length 150 cm: —————

Scan-length 180 cm: - - - - -

Scan-length 200 cm: ······

A. Symmetric positioning.

B. Asymmetric positioning, rear end of line source at 100 cm from centre.

C. Asymmetric positioning, rear end of line source at 90 cm from centre.

D. One-meter-arc geometry.

An example of the use of such an approximation is shown in Figure 15. Human subjects have different heights, for instance children and adults. The following questions then may arise: "Should all subjects be positioned in the middle of the scan, symmetrical positioning? Or should we have a reference point, for instance the eyes, in relation to the scan-end, asymmetrical positioning?" Figure 15 shows results of calculations using formula (7) for various source lengths and for scan-lengths 150, 180 and 200 cm, with symmetrical and asymmetrical positioning. The ordinate values in Figure 15 show the efficiency in relation to that of the one-meter-arc geometry.

We see that asymmetrical positioning gives results less dependent on body length than symmetrical positioning. For example, by positioning the rear end of the line 90 cm from the center, the response within 5 % will be independent of source length from 70 cm to 200 cm. The symmetrical positioning would have a rather linear dependence on "body length". It corresponds to approximately 2 %, 1.2 % and 0.7 %, per 10 cm variation of the source length, for 150, 180 and 200 cm scan-length, respectively. The lower counting efficiency with asymmetrical positioning, would in practice, usually be an insignificant draw-back.

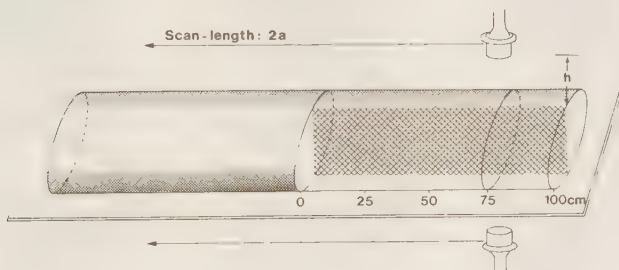
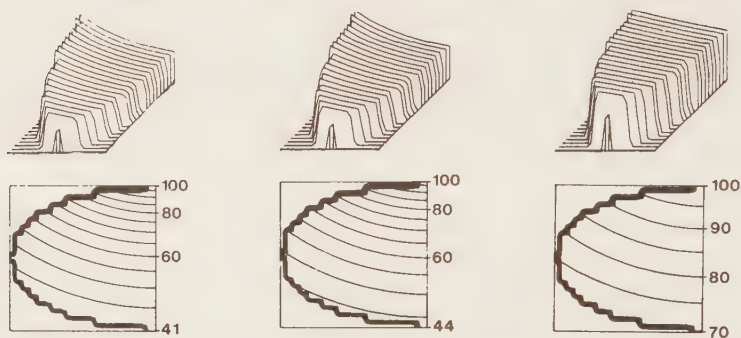


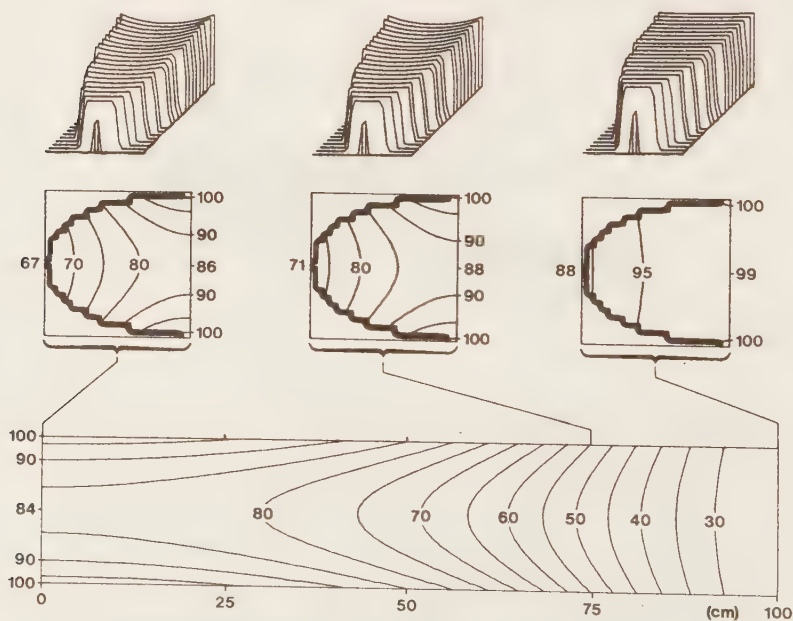
Figure 12. Schematic illustration of the dimensions of phantom and measuring geometry used for the theoretical calculations in Figures 13. The sagittal (vertical) plane, square-hatched, is indicated as well as the elliptical transversal sections at 0 cm, 75 cm and 100 cm from the plane of scanning symmetry. The dimensions of the phantom are; length: 200 cm; major diameter: 40 cm; minor diameter: 20 cm. The scan-length, $2a$, the distance, h , from detector to phantom and the linear attenuation coefficient, μ , are varied. In Figure 13, for double-detector scan, the lower and the upper detectors are supposed to have the same distances from the phantom.

Figure 13. Contour-maps and isometric illustrations of total calculated variation in the longitudinal (sagittal) plane and three transversal planes as explained in Figure 12. Owing to the symmetries only half of the sections are displayed. The varied parameters are given in the lower right hand corner. Transversal variation is presented separately for single-detector-scans and symmetrical double-detector-scans.

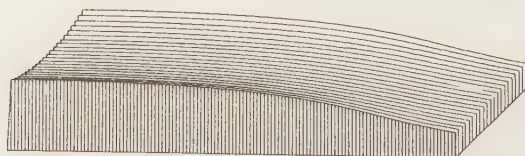
Transversal variation; Single-detector-scan



Transversal variation; Double-detector-scan



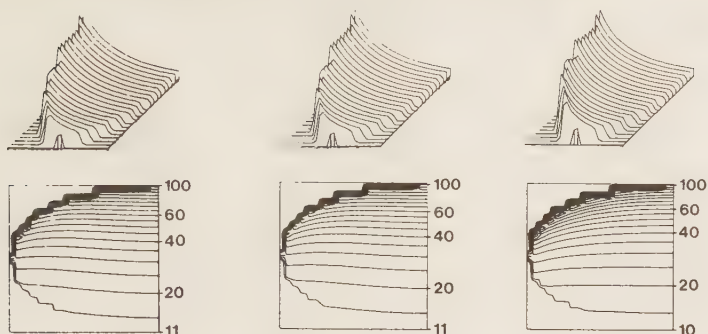
Longitudinal variation; Double-detector-scan



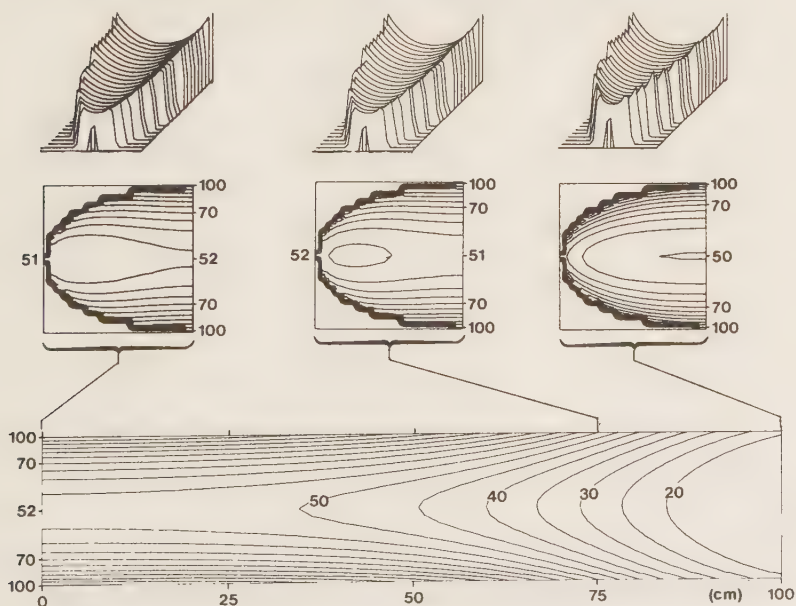
2a: 150 cm
d: 60 cm
h: 20 cm
 μ : 0 cm⁻¹

Figure 13A

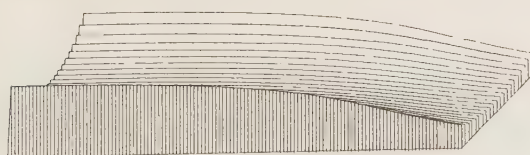
Transversal variation; Single-detector-scan



Transversal variation; Double-detector-scan



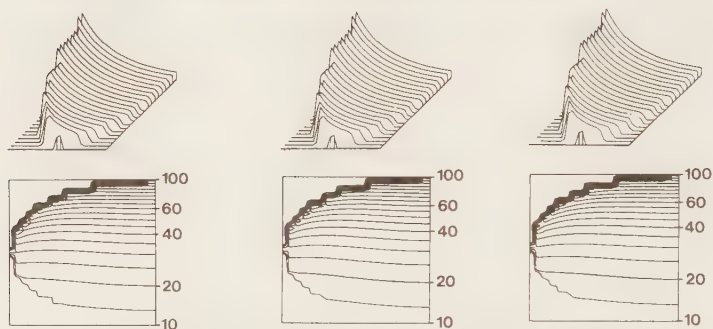
Longitudinal variation; Double-detector-scan



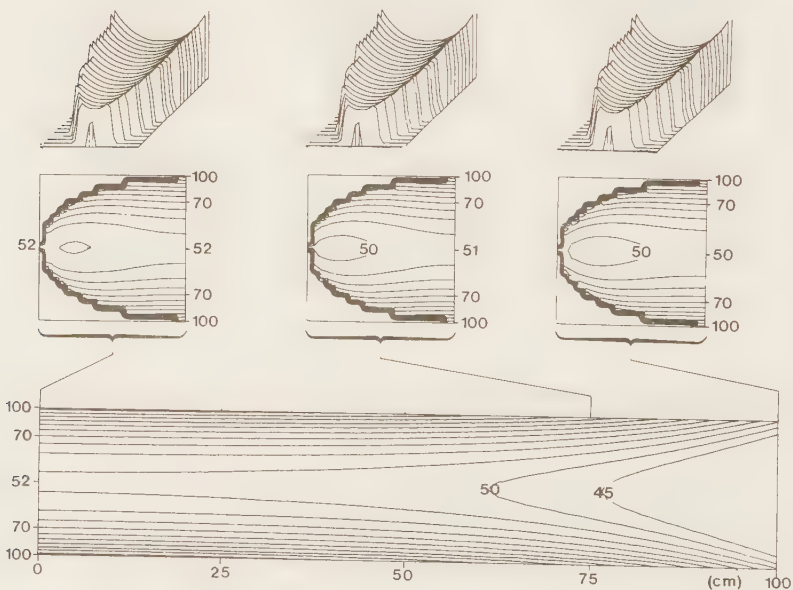
2a: 150 cm
d: 60 cm
h: 20 cm
 μ : 0.055 cm⁻¹

Figure 13B

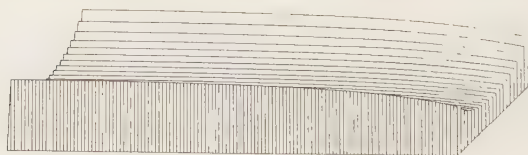
Transversal variation; Single-detector-scan



Transversal variation; Double-detector-scan



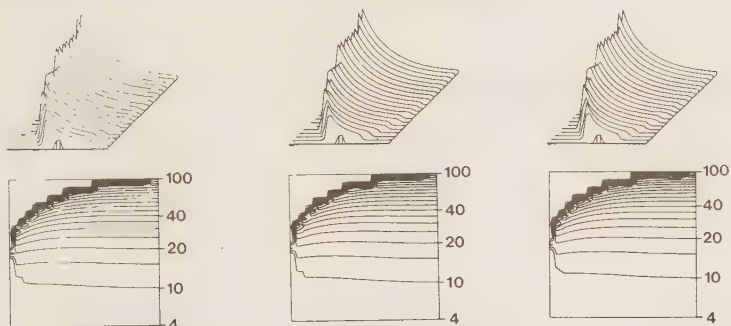
Longitudinal variation; Double-detector-scan



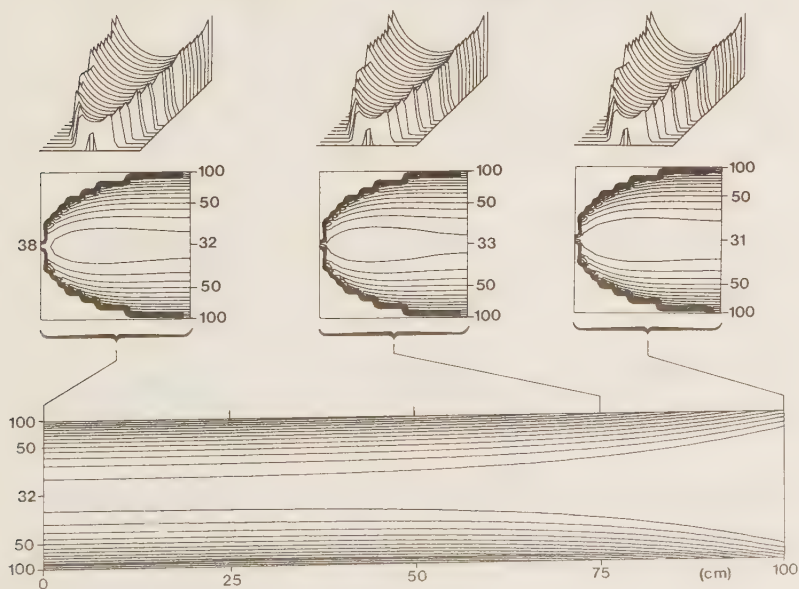
2a: 200 cm
d: 60 cm
h: 20 cm
 μ : 0.055 cm⁻¹

Figure 13C

Transversal variation; Single-detector-scan



Transversal variation; Double-detector-scan



Longitudinal variation; Double - detector - scan

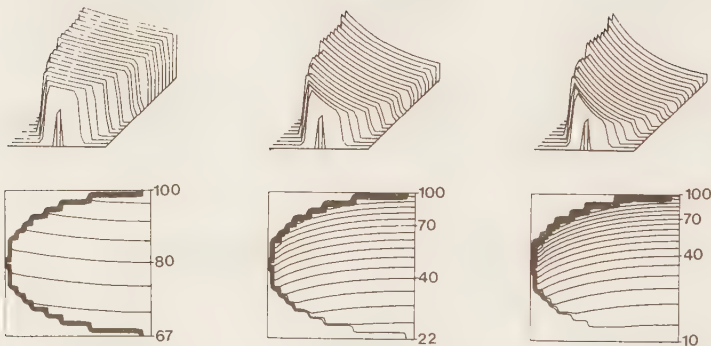


2a: 200 cm
d: 60 cm
h: 20 cm
 μ : 0.095 cm⁻¹

Figure 13D

One-meter-arc

Transversal variation; One - side



Transversal variation; Two-sides

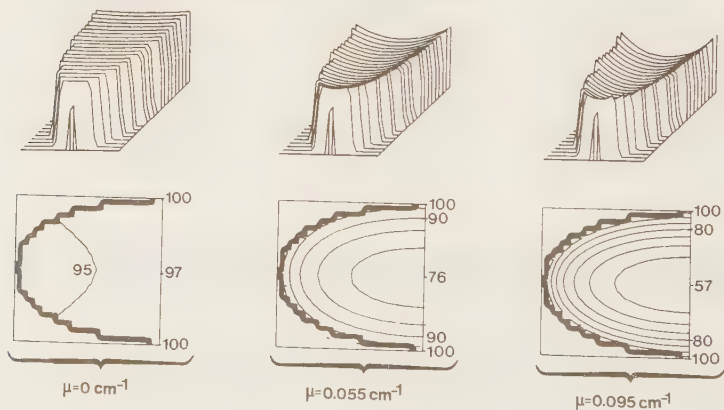


Figure 14. Transversal variations calculated for one-meter-arc geometry. The phantom is supposed positioned analogous to those in Figures 12 and 13, with prone and supine "measurements". The centre of the elliptic sections are supposed to be at 0.9 m from the detector. Calculations are made for the linear attenuation coefficients: a) 0 cm^{-1} , b) 0.055 cm^{-1} , c) 0.095 cm^{-1} .

3. APPLICATIONS

3.1. Introduction.

Whole-body counting is widely used for assessment of the activity of radionuclides within the human body. The applications of the different counting techniques are mainly in two fields:

- * Radiation protection and
- * Diagnostic and research procedures in medicine

3.2. Applications in radiation protection.

In radiation protection it is important to be able to identify radionuclides, as well as to quantify their activities which may have been unintentionally introduced into the body, or become attached to the body surface. In several industrial, research and medical uses of radionuclides, the work may be associated with body contamination of small amounts of identified radionuclides that have well-known chemical forms and metabolisms. In such cases, when the nuclide distribution in the body is known, and the radiation dosimetry can be studied in advance, it can often be appropriate with activity assessment with uncertainties of, for example $\pm 10\%$ and even up to $\pm 50\%$.

In other cases, more stringent counting techniques are needed. For instance, if radionuclides of unknown chemical compounds and metabolisms are involved, and when the absorbed doses can be of such magnitude that administrative or medical measures must be considered. Studies then may involve accurate repeated measurements with different-time intervals to get information on body retention and excretion rates. In such instances, accuracies within a few per cent may be needed. To achieve this goal, techniques with responses independent of body size, shape and activity distribution are needed. Alternatively, it should be possible to apply objective correction factors in relation to anthropometric parameters.

3.2.1. Contamination of the biosphere by fallout-radionuclides.

After 1950 it was realized that nuclear weapons tests resulted in a world-wide spread of fission-product radionuclides in the biosphere (Miller och Marinelli, 1956; Sievert et al., 1956; Anderson et al., 1957). This occurred through local, tropospheric and stratospheric fallout. Most of these several hundreds of fission product radionuclides are short-lived and of minor consequence in non-war conditions. Some elements, such as strontium, yttrium, zirconium, niobium, ruthenium, rhodium, iodine, lanthanum and caesium, have isotopes that are produced with a high yield and have half-lives long enough to be transported around the earth. Especially the long-lived radionuclides, Cs-137 and Sr-90, were spread throughout the world by stratospheric fallout.

The various radionuclides reached man through different food-chains. Especially Cs-137 and Sr-90, but also several other radi-

onuclides, could give a significant committed dose equivalent to man (Persson, 1970). It was especially alarmingly high in humans in several countries around the Arctic Circle. This fact warranted extensive investigations by several research groups. The research had two main purposes, namely to clarify

- * The routes of different food-chains to man and

- * The metabolism in man

In Sweden, a research group at our laboratory made important contributions to clarify the Scandinavian food-chains involved for Cs-137 and other radionuclides (Lidén, 1961; Lidén and Andersson, 1962; Svensson and Lidén, 1965; Persson, 1970; Holm and Persson, 1975; Mattson, 1975). Work was also done in collaboration with scientists in Finland (Miettinen et al., 1963).

3.2.2. Field whole-body counting technique (II).

In order to be able to make these measurements in humans at long distances from the established laboratories, it was necessary to have a simple whole-body counting equipment that could easily be transported. In PAPER II, SEMI-PORTABLE WHOLE-BODY COUNTER FOR CESIUM 137 AND OTHER GAMMA-EMITTING ISOTOPES, a unit is described in detail that was used for the investigations in northern Sweden as well as in northern Finland. A similar unit was later used by the Finnish group (Miettinen, 1964).

The unit was basically a 42 cm-chair counter. The routine field-techniques could therefore also be based on the experiences of calibration and general counting performances that were well established at our laboratory (Cederquist and Lidén, 1962) and others (IAEA, 1964; IAEA, 1970). For the ambulatory work, a compromise was made between the more ideal counting geometry of the scanning-type method and the more easily constructed and assembled geometry of the chair-type. It also gave an easily reproducible measuring geometry for repeated studies. The choice was specially suitable for counting the rather even body distribution of Cs-137, that was the main subject of interest.

In PAPER II, measuring conditions are analyzed that are related to the elevated and less stable field backgrounds found at various locations due to the comparatively weak background shield. The background depression caused by the subject in the counting position is examined for various energy ranges. It was found that an increase in background count-rate appeared instead below 300 keV, due to scattering in the subject's body. Calibration of Cs-137 for various body weights was obtained by phantom studies and by comparison with the iron room whole-body counter in Lund. It was found that the total uncertainty in the field environment could be estimated to be about 0.6 kBq Cs-137 at the level of 95% confidence. In consideration of the rather high Cs-137 body burdens of reindeer meat-eating people, the accuracy was considered adequate. For a typical male reindeer-breeder (1961-1966), with a body content of 30 kBq Cs-137, and a typical female control subject, with for example 1.5 kBq Cs-137 this corresponded to uncertainties of 2 % and 40 %, respectively, for counting times of ten minutes.

3.2.3. The Enhanced Radiocaesium Levels in Northern Sweden (III,IV).

Unexpectedly high Cs-137 body-burdens were found in people in northern Scandinavia, as reported by Lidén, 1961. The research following this discovery showed an intimate relation between the activity concentrations in fallout, lichen, reindeer and man (Miettinen et al., 1963; Svensson and Lidén, 1965; Lidén and Gustafsson, 1966). Of great importance for the evaluation of this arctic food-chain was the direct confirmation of the levels in man. Field measurements of selected groups, as reported in PAPER III, THE ENHANCED RADIOCAESIUM LEVELS OF PEOPLE IN NORTHERN SWEDEN, provided a baseline for the final explanation of the high body-burdens (as also reported by Miettinen et al., 1963; Naversten and Lidén, 1965; Hanson and Palmer, 1965; and others).

The metabolism of caesium in man is of particular importance, since Cs-137 has a high fission yield and also a long physical half-life ($T_{1/2} = 30$ a). Ten years after the fission, it constitutes about a fifth part of the remaining fission products (Hunter and Ballou, 1951). Although delayed due to the continuing atmospheric debris and due to the transport in the ecological system, the equilibrium level that will be built up in man is finally dependent on the biological half-life in humans. The studies of the metabolism of radiocaesium, such as those reported in PAPER IV, HALF-LIFE STUDIES OF RADIOCAESIUM IN HUMANS, constitutes the last link of great importance for the absorbed dose calculations. Gustafsson, 1969, estimated that the committed dose equivalent for Swedish reindeer breeders, of internal deposition, coming from existing fallout of Cs-137 was about 10 mSv. In PAPER IV, it is shown that the metabolism has several elimination components. The half-life of the main component was found to be 60 to 90 days for adults, but only 25 days for two babies and 32 days for a mother before partus, as also reported by Bengtsson et al. 1964. The half-life was thus found to vary with age and different health conditions. Richmond et al., 1962; Miller, 1964c; and several others had found half-life-values up to about 150 days. The cause and degree of the variability of the half-life caused some controversy in scientific circles, as reported by Lidén, 1964. Little has later appeared in the literature that can further clarify the subject. Richmond, however, reported in 1980 half-life values for five mammalian species. He found an interspecies correlation to the body surface, with values varying from about 1 day for mouse to over 100 days for man. This result might support our finding in PAPER IV and indicate that caesium turn-over is rather highly dependent on the general metabolic rate.

3.3. Applications in medicine.

Medical uses of whole-body counting can involve singular measurements, as for total body potassium determination, but prolonged (repeated) retention measurements are often utilized, e.g. for kinetic studies of vitamin-B12 (Reizenstein et al., 1966), iron (Price et al., 1972) and calcium (Knop et al., 1977). The retention curve in kinetic applications is often matched to a pool-compartment model. For complex compartment systems accurately (within few per cent) measured data are needed (Wotton and Reeve, 1980).

In kinetic studies with intravenously administered Fe-59, the same count-rates must be obtained irregardless of if the iron is plasma-bound "evenly" distributed in the body, or if it is at some later stage incorporated in the bone marrow or the spleen, or later again redistributed as labelled red blood cells. Saito et al., 1964, showed with a one-meter-arc geometry technique that Fe-59 translocation resulted in differences mainly due to attenuation of the order of 10%. Price et al., 1962, got similar effects for the chair geometry.

The metabolism of iodine is another example of extreme redistributions which is of relevance for the discussion in this thesis, for instance, i.v. given inorganic I-131 or protein bound I-131 may initially be evenly distributed in the body. It can later be accumulated in the small, superficially, located thyroid. I-131 labelled thyroid hormones are then released to the vascular space and ultimately metabolized in the liver. Cederquist and Lidén showed 1962 that two different whole-body counting methods, the 42 cm-chair and the scanning bed, apparently had different retention values after i.v. injection. The scanning-bed method gave results in good agreement with urine excretion data. Related to the initial measurement, the chair-geometry erroneously gave about 100% too high values. This was explained by the changed geometry and attenuation in the body. This large effect is further experimentally confirmed in PAPER I, TABLE I. Additional improvements of the measuring accuracy can be obtained by counting the scattered photons in a similar way to that as proposed Dudley and ben Haim as mentioned in Section 2.1. Applying this method to I-131 retention studies, this was splendidly demonstrated by Gibbs et al. (1970) using a pulse-range of scattered photons instead of the full-energy-peak range. Cook et al. (1970) used the same principle for Fe-59. An explanation for the improvement may be inferred from the shape of spectra from different organs in a phantom, see Figure 5 in this thesis. Corresponding experimental results for Cs-137 are also given in Figure 18, PAPER I. On the other hand, changed count-rate in the full-energy-peak due to redistribution, can also be used diagnostically, as showed by Cederquist (1964) for bone-seeking radionuclides.

Examples given above and in the following text show that advanced counting techniques are often required with accuracies within a few per cent. In research and diagnostic uses, the activity content of different organs may vary within the patient quite differently in different individuals in an unknown manner. A proper interpretation of the counting results must still be possible.

3.3.1. Vitamin B12-absorption measurement (V).

Measurement of the absorption of orally given vitamin B12 labelled with radioactive cobalt isotopes is a further example of a useful clinical application of whole-body counting. Several other methods exist for the evaluation of B12-absorption. These involve investigations of blood, excreta or liver up-take. Whole-body counting is, however, capable of giving a direct physiological measure of the gastro-intestinal absorption. The technique is based on the fact that B12 is slowly eliminated from the body, while non-absorbed B12 normally is excreted within a week. There are obvious advantages of whole-body counting: no prob-

lems of excreta collection, no effect from possible renal dysfunction, and no need for non-physiological "flushing dose" of B12, that can interfere with other haematological investigations. The examination can be done on an out-patient basis, but a draw-back is that normally there is no final answer until a week after administration.

Orally given vitamin B-12 labelled with Co-57 or Co-58 should give count-rates independent of whether the activity is confined to the gastro-intestinal tract or is absorbed and plasma-bound, or, to an uncertain fraction, is incorporated in the liver. The measuring conditions of Co-57 labelled B12 is studied in detail in PAPER V, THE STUDY OF 57Co-VITAMIN B12-ABSORPTION USING A WHOLE-BODY COUNTER, where the whole-body counter is described. Some further details are given in Figure 6b, section 1.9. Special efforts have been made to study the various pulse-height distributions for different positions of volume sources. It has been done with a masonite phantom in order to resemble the attenuation and scattering of photons in the human body. The results of measured longitudinal and vertical variations confirm those theoretically calculated in PAPER I.

Two different pulse-height regions are analyzed. It is shown that the counting response is less dependent on the Co-57 distribution if pulses in the energy range 43-95 keV are used instead of pulses mainly in the full-energy-peak, 95-150 keV. Measurements on control subjects and patients during the first hours (PAPER V, TABLE 4), also confirm that the low-energy region gives more constant results, as the given 57Co-B12 moves in the gastro-intestinal tract. A large fraction is then incorporated in the liver during the first week. The high energy range then gives about 10% higher absorption values than the low energy range. This could well be due to a difference in the average depth of the intestine and liver. From Figure 17, PAPER I, it is seen that, at a depth of 5 cm, a change of only 1 cm can change the response by about 5 % if the μ -value is about 0.09 cm^{-1} . It was also found for one control subject that the chair-geometry can give an error that is significantly greater than that of the dual detector scanning-bed geometry. Tappin et al. (1966), using a multiple detector-bed system, also demonstrated that redistribution of orally given 58Co-B12 had combined geometrical and attenuation effects resulting in errors of the order of $\pm 10\%$ within 3 hours after administration. From the pooled data for 122 patients it is possible to calibrate the system. The sensitivity (given in PAPER V as counts per minute for each microcurie) of Co-57 in the gastro-intestinal tract is shown to vary with body weight - less for the low-energy range than for the high energy range. The spread of data points is also less in the former case.

All these findings indicate that the dual-detector scanning system effectively reduces potential errors of activity redistributions. The use of an energy range of scattered photons decreases the fictitious attenuation coefficient of 122 keV photons of Co-57. This fact improves the possibility of using this rather low photon energy.

In the clinic it is desirable to get a differential diagnosis between pernicious anaemia and other causes of B12 malabsorption on only one test occasion. Reizenstein et al. (1961) used a double-tracer technique with Co-58 and Co-60. One of them was tagged to B12 and the

other to B12 and "intrinsic factor". Co-60, however, gives a rather high absorbed dose to the liver. It is therefore of potential importance to be able to use Co-57 and Co-58, instead. Boddy et al. (1969) showed that it is possible to reliably measure ^{57}Co B12 retention in the presence of ^{58}Co -B12 in the body. This is possible since the B12-absorption in patients with pernicious anaemia differs so distinctly from that of control subjects, as is shown in PAPER V, TABLES 2 and 3, as well as by others (Boddy et al., 1969; Cottrall and Trott, 1970; Simpson and Shearman, 1968; Tappin et al., 1966). Tait and Hesp (1976) also showed that, by calibration similar to that in PAPER V, FIGURE 5, a diagnostic answer can be obtained by only one measurement for patients with low absorption, e.g. pernicious anaemia with about 10 % or less. In such cases the error would be only about one per cent-unit, even if the patient was not counted before and after the administration, at "100 %". It would only need activity assessment of the capsule to be swallowed and of the patient at about one week after administration.

3.3.2. Total body potassium determination.

Of all applications of whole-body counting total body potassium (TBK) determination is the one most generally established. The principle is described in PAPER VI, A STUDY OF TOTAL BODY POTASSIUM DETERMINATION USING A WHOLE-BODY COUNTER. The technique started around 1950 as an off-spring of determinations of the content of radium in humans, using large ionisation chambers (Sievert, 1951; Burch and Spiers, 1953). Since the body activity of K-40 is extremely low, adequate precision and accuracy could not be obtained until the techniques with large scintillation detectors were developed. The Los Alamos group pioneered with a large annular liquid scintillator (Reines et al., 1953). They then further elaborated this technique (Anderson and Langham, 1959, 1961; Allen et al., 1960; Anderson, 1963) and several other large organic scintillation systems became clinically available (Heinrich et al., 1965, 1966; Delwaide, 1970; Tauxe and Orvis, 1966; Sköldbörn et al., 1972). In the same time-period, several techniques were also developed using large NaI(Tl) scintillation detectors. Of these, some groups made important methodological investigations of techniques for body potassium assessment (Remenchik and Miller, 1961; Miller and Remenchik, 1963; Miller et al., 1967; Remenchik et al., 1967; Forbes et al., 1961, 1963, 1968, 1981).

The determination of TBK using its natural isotope, K-40, has unique problems involved. The K-40 concentration in the body is very low and there is no other method for IN VIVO determination of it. It has therefore been something of a challenge for researchers, 1) to prove that the whole-body counting method has a good and adequate accuracy, and 2) to establish generally useful normal values for groups of people. Reaching these goals will finally determine its usefulness in medicine.

Normal ranges have been compiled mainly for adults (Anderson and Langham, 1959; Oberhausen and Onstead, 1965; Lorimer et al., 1965; Delwaide, 1969; Ellis et al., 1974). Novak, (1973) and Oberhausen et al., (1965) have also especially investigated normal values for children. Related to body weight, age and sex, there is a wide spread (about 25 %). It is therefore generally not so useful to evaluate just

the measured TBK as normal or not, for individual subjects. This is due to the wide constitutional variations in people in general regarding, for instance, the metabolism and degree of obesity. If TBK is moderately changed, correlation to anthropometric data, lean body mass, body water etc. are needed to eliminate effects of, for instance, varying fat and skeletal mass (Allen, 1960; Boddy et al., 1972, 1974; Noppa et al., 1979; Pipe et al., 1979).

Ellis et al. (1974) statistically analyzed TBK in a group of 3400 normal subjects. They found a formula to get a predicted value, K(p), of body potassium:

$$K(p) = c.W^{1/2}.H^2 \quad \dots(9)$$

K(p) = predicted normal potassium, (g).

W = weight, (kg).

H = height, (m).

A = age, (a).

c = 5.52 - 0.014xA; for males.

c = 4.58 - 0.010xA; for females.

Applying this formula to the results on groups of patients with 18 different diseases, they found average ratios of TBK/T(p) from about 1.14 (Turner's syndrome) to about 0.84 (disuse-osteoporosis), with standard deviations for individual groups of about 0.12. There was, thus, correlation of the ratio to different pathological states. Further refinements of the reference formula, however, for instance by inclusion of other anthropometric data for the prediction of body potassium, is desirable. It is necessary in order to match the high accuracy attainable with whole-body counting techniques. Such a formula must cover all ages, from newborn (Garrow, 1967; Hukkuo et al., 1972; Novak, 1973) to old age (Lye et al., 1976; Lye and Winston, 1979).

Chandra et al. (1979) also used the ratio TBK/K(p) on patients with chronic lymphatic leukemia. They found an excess of potassium in patients in Stages III-IV of 10 to 20 %. Significant increases were also found in Stages I and II. The mean of Stage I differed by 3.5 % from the mean of controls. Since this could be a method of staging and follow-up of these patients, it indicates the degree of correlation accuracy that is needed.

Besides the real variations of body potassium, there may be systematical measuring errors:

- * Differences in calibration from laboratory to laboratory, and
- * Insufficient correction of response for varying body constitution.

The published data, as referred to above, of potassium concentrations, g K/kg, on large populations, are somewhat inconsistent, indicating different calibrations. Alternatively, the population samples are not comparable. Somewhat more homogeneous values can therefore be anti-

cipate if suitable correlation parameters are agreed upon.

The second type of errors have lead to discussion in many investigations (Burkinshaw, 1967; Forbes, 1968; Hukkuo et al., 1972; Meneely et al., 1962; Miller et al., 1967) as well as in this thesis, specially for TBK in PAPER VI. Some clinical applications involving lean body mass or cell mass assessment are dependent on an adequate correction for this error. For instance, Forbes et al. (1961) suggested the TBK is an estimator of the mass of body fat, based on the fact that fat contains very little potassium. Cosmetically obese subjects on a starvation diet can be followed at certain intervals. Since each subject will be his own control, most of the problems, concerning populations mentioned above, are eliminated. In this example, however, varying response with body stature, as well as long-term stability of the equipment, are essential problems to overcome, as discussed in PAPER VI. Even with this under control, results must be cautiously judged since there are indications that obese subjects have low intracellular potassium concentration (Colt et al., 1981).

From a methodological point of view, most laboratories have correlated their calibration to weight (W) or height (H), or to different combinations of these parameters. In this thesis, PAPER VI, best correlation was obtained with $(W/H)^{1/2}$, as is used by several other investigators. Smith et al. (1979) compared the results from a scanning multi-detector liquid scintillator system with that of a multi-detector array NaI(Tl) system. These counters had similar geometry, and they also got almost identical correlation of the calibration factor to $(W/H)^{1/2}$. Similar variation was also found for a bed unit with plastic-detector blocks (Arvidsson et al., 1972) and a chair-plastic-detector system (Burkinshaw 1967). In fact very different types of counters; Los Alamos, HUMCO II, and a NaI(Tl) chair geometry, respectively, got similar correlation to body weight (Dean, 1965). This shows that self-attenuation in the body is the major cause for the response variation. Cohn et al. (1969) measured the transmitted photons of Cs-137 along the body to correct for the internal self-attenuation by the use of geometrical mean-method according to Genna (1966) and Sorenson (1974). For potassium in a series of eight subjects (66 to 146 kg) they got a constant response with a coefficient of variation of less than 4%.

The result of the total body potassium measurement should be independent of whether or not it is a hard-labourer with heavy chest and back muscles, a long-distance runner with well developed muscles in the legs or an obese patient with a thick girdle of fat around the body. Miller and Remenchik (1963) argue that, besides effects of individual habitus, also significant attenuation errors can result using the technique comparing K-42 and K-40, if a significant amount, maybe 10%, of the body potassium is "non-exchangeable" e.g. in the skeleton (ICRP, 1975). However, Hartsuck et al. (1969), found quantities on samples of ribs of two patients, which, if extrapolated to the total skeleton, would correspond to only two per cent of total body potassium. About half of that was exchangeable within 40 h. Our finding in PAPER VI, Figure 4, where no significant time-dependence could be detected, is supported by the work of Hartsuck and his collaborators. The same result was also obtained with the whole-body counter shown in Figure 6c.

These results show that, for normal-weighted subjects measured with scanning-systems, K-42 is to be regarded "macroscopically" fully exchangeable within 24 hours.

These examples show that, from physical and methodological points view, there has been a great demand for detailed basic studies of the reasons for response variations obtained and the optimal parameters to be used for accurate whole-body counting, especially with NaI(Tl) systems, as has been treated in this thesis.

4. GENERAL SUMMARY AND CONCLUSIONS

Techniques for the determination of whole-body radioactivity in man using uncollimated NaI(Tl) detectors have been studied. In particular, the geometrical performances and the source self-attenuation of photons have been evaluated for the scanning-bed geometry and for the chair-geometry. Theoretically, it is shown that the attenuation effects are generally dominating, for full-energy-peak pulse-range methods. If double-detector scanning-bed systems are utilized, a good evening-out of redistributional effects is theoretically anticipated and is verified by the experiments.

The counting efficiency in relation to the length of the scanning-orbit and its relation to the distance from the source to the scanning-orbit is given. It is theoretically shown that scan-lengths from 150 cm to 200 cm are adequate. For double-detector systems the distance between the detectors, on each side of the human subject, should be about 60 cm. Increasing the distance would only lower efficiency of the system without significantly lessening redistributional effects in humans, since the attenuation is dominant for full-energy-peak methods. Even with an integral pulse-height range from 100 keV up to and including the full-energy-peak there will be fictitious linear attenuation coefficients of significant magnitude. By the use of certain experimentally selected scatter-energy pulse-height ranges, however, normally not including the full-energy-peak, and the use of scanning double- or multiple-detector systems, it is possible to get count-rates that are independent of source depth in large volumes, even in human subjects.

For the application in radiation protection studied, the artificial radioactivity of Cs-137 in humans, it is shown, that a cheap and simple whole-body counting unit could be transported and used at various places, distantly from the home-laboratory. Backgrounds and its variations were studied, and although it was high, adequate counting precision and accuracy could be obtained in the field-investigations. In these studies, extremely high body burdens of Cs-137, were found particularly in reindeer-breeding Lapps. For men, in the period 1961-1966, it was frequently 50 to 100 times the "normal" body burden of Cs-137. The elimination rate of the radionuclide in humans was studied both with the field-system and the stationary whole-body counter in Lund. The biological half-life was found to be short in comparison with the results reported by other investigators. There are also indications that the half-life was highly dependent on the metabolic rate of the body.

The clinical uses studied, ^{57}Co -B12 absorption and total body potassium determination, have confirmed that the scanning-methods have a good and adequate accuracy. Using ^{57}Co , it is shown that whole-body counting methods are possible for photon energies down to about 100 keV. This finding is important owing to the common contemporary uses of low-energy photon emitters (e.g. $^{99\text{m}}\text{Tc}$ and ^{123}I) for diagnostic methods in nuclear medicine.

Using the naturally occurring K-40 and the short-lived isotope K-42, a method of total-body potassium determination was studied. The scanning-bed geometry is found useful also for this application. A detailed analysis of the counting method and its medical applications shows

that a very high degree of accuracy is needed. For example, a coefficient of variation around a few per cent at a 95 % confidence level is desirable to distinguish some pathological states. In order to obtain a full medical use of this simple method further investigations of particularly the reference levels in relation to suitable constitutional and physiological parameters should be performed.

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PANEL PROCEEDINGS SERIES

CLINICAL USES OF WHOLE-BODY COUNTING

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SOME ASPECTS OF WHOLE-BODY COUNTING GEOMETRIES

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Some typical geometrical arrangements often used with NaI(Tl) crystals are discussed with particular reference to their usefulness for clinical applications. The following types of whole-body counters are treated:

- (1) The arc geometry,
- (2) The chair geometry,
- (3) The bed geometry with an array of fixed detectors,
- (4) The scanning bed geometry with one or several detectors.

THE ARC GEOMETRY

When working on the problem of body radium detection in the 1930s Evans [60] realized that an arc technique was ideal from a geometrical point of view in order to get a response as independent as possible of the radioactivity distribution in the body, especially along the long axis of the body. In the beginning Evans' technique was used with a G-M tube in the centre of an arc with a radius of 1 m. The patient was measured once with the curvature along the ventral aspect of the body, touching the forehead, shoulder, abdomen, knees and toes, and once with the curvature along the dorsal aspect of the body touching the head, shoulder, buttocks and heels. By measuring a standard source, once on the arc in air and once on the distal surface of the patient, it was possible to assay the body activity fairly quantitatively.

Later Marinelli et al. [121] modified the arc technique for a NaI(Tl) crystal, 3.7 cm in diameter and 5.6 cm thick, as a sensing unit. For the efficiency variation caused by the attenuation of photons in the body, they used fictitious attenuation coefficients and scattering correction factors obtained from measurements of a small Ra-source at different depths in Masonite phantoms. This technique made it possible to assay body activities of γ -ray emitting nuclides with notably increased accuracy and sensitivity. Later several investigators have used similar arc techniques with larger and more sensitive detectors (Fig.1).

The main disadvantage of the arc technique with a radius of, say, 1-2 m, is the low yield of pulses because of the long distance between the counter and the radioactive material. The uncomfortable posture of the patient, sometimes combined with a long counting time, also restricts the clinical value of the arc technique for whole-body counting.

THE CHAIR GEOMETRY

Very soon it became evident that a more sensitive and more comfortable counting geometry was highly desirable. In the middle of the

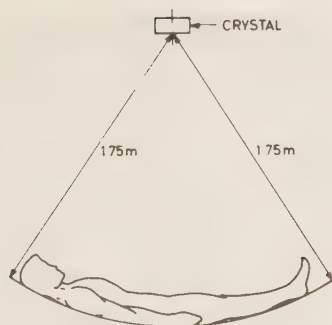


FIG.1. Schematic representation of the crystal-subject arrangement in a 1.75-m arc [136]

1950s the group at Argonne National Laboratory under L.D. Marinelli introduced a geometry later called the Marinelli chair, Argonne chair, standard chair, tilting chair or 42-cm chair. This whole-body counting technique has been used with cylindrical NaI(Tl) crystals of varying size. The subject sits in a chair with the hips and the knees flexed 90° . The distance from the centre of the plane surface of the crystal to the back and to the seat of the chair is 42 cm (Fig.2). In the counting position the chair is usually tilted 45° or 55° backwards [135, 136, 147].

In this counting geometry the entire body except the lower legs is roughly equidistant from the crystal. The average distance is only about a third of that in the 1-m arc, which means higher sensitivity and a shortening of the counting times. Furthermore the patient can sit in a comfortable chair during the measurement. For potassium in equilibrium in the body Miller [135, 136] has shown that the accuracy of determination of body potassium for adults weighing between 50 and 100 kg is about $\pm 5\%$.

For routine clinical follow-ups of body retention of a radionuclide the chair technique is less suitable. For instance, after oral administration of a nuclide, the response to the body radioactivity may vary substantially in association with its redistribution during resorption, metabolism and excretion. Miller and Marinelli [132] gave two μCi of a ^{42}K solution to several subjects. They were followed for 50 h with frequent measurements in the chair. The response (pulses/unit time/body γ -ray emitted) as a function of time was calculated from parallel measurements of all excreta and by adequate correction for physical decay (Fig.3). Initially, when the activity was still concentrated within the abdominal cavity, a fairly high count-rate was recorded.

After 10 h, when the activity was rather evenly distributed in the body, the count-rate was only 55 to 75% of the initial values. Similar results were obtained in several clinical applications of chair geometry whole-body counting in investigations of patients with various radionuclides [31, 32, 187]. For ^{85}Sr (a bone seeker) the change of the response due to redistribution may be as much as about 30% within the first 10 d after IV injection [31]. Miller [139] has reported results on radium contamination

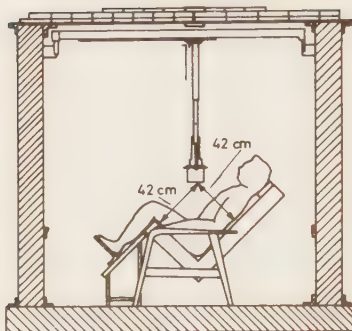


FIG. 2. Schematic representation of the crystal-subject arrangement in a 42-cm chair [147]

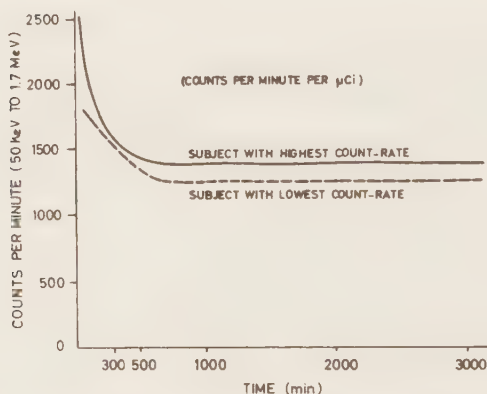


FIG. 3. Response variation in 42-cm chair due to redistribution of ^{42}K after oral administration [132]

in the skeleton indicating that the chair technique may give results with an error of about 15%. For such an extreme case as ^{131}I , where the residual activity is confined almost exclusively to the thyroid glands, the geometrical effect and the attenuation effect together may change the response by about 100% [31]. Phantom studies [147] also showed clearly that the clinical use of the chair technique is limited if activity redistributions may occur (See Table I).

It is evident that adequate precautions must be taken for each clinical application of whole-body counting with the chair technique. Some investigators [39] have calculated (during the initial period after administration of a radionuclide) the retention from the results of direct whole-body counting as well as of excreta sample counting. At the supposed end of the redistribution period the results of whole-body counting are normalized to those of the excreta counting. Furthermore, by a geometry with the crystal higher above the chair, the pure geometrical effects of the redistribution are certainly diminished [39]. However, the effects due

TABLE I

RESULTS FROM PHANTOM STUDIES

The response in the photopeak energy ranges of ^{131}I , ^{132}Cs and ^{47}Ca in the thyroid, the bladder and the liver, normalized to the response obtained when the activity was uniformly distributed in the whole body, as obtained from measurements with a 12.5 cm $\times$ 10.0 cm NaI(Tl) crystal in both 42-cm chair geometry and 144/45-cm scanning-bed geometry. The statistical accuracy is given as 2 S.D.

Nuclide	Geometry	Whole-body	Thyroid	Bladder	Liver
^{131}I (0.36 MeV)	Chair	1.00 ± 0.02	1.73 ± 0.07	0.74 ± 0.03	1.84 ± 0.07
	Scanning bed	1.00 ± 0.02	0.96 ± 0.04	0.98 ± 0.04	1.07 ± 0.04
^{132}Cs (0.67 MeV)	Chair	1.00 ± 0.02	1.68 ± 0.08	0.80 ± 0.04	1.92 ± 0.09
	Scanning bed	1.00 ± 0.02	0.99 ± 0.05	1.05 ± 0.05	1.10 ± 0.05
^{47}Ca (1.31 MeV)	Chair	1.00 ± 0.03	-	0.83 ± 0.04	2.00 ± 0.10
	Scanning bed	1.00 ± 0.07	-	1.11 ± 0.04	1.13 ± 0.06
Efficiency ratio		1.69 ± 0.03	-	-	-
$\frac{\text{chair}}{\text{scanning bed}}$ (per crystal)					

to changed attenuation at redistribution within the body cannot fully be taken into account.

Chhabra [34] reported a new improved chair geometry, the 50-cm arc chair (Fig. 4). He showed that with a 8 in. $\times$ 4 in. NaI(Tl) crystal this geometry is less dependent on the radioactivity distribution than the standard chair. Chhabra compared these two geometries with the 1-m arc. Patients were given ^{131}I (in gelatine capsule) and vitamin B_{12} labelled with ^{58}Co . The retention was measured in the three geometries mentioned. It was found that the results of the 50-cm arc chair technique agreed well with those of the 1-m arc technique, while the standard chair technique after one day constantly gave about 15% higher apparent retention values. The response variation of ^{137}Cs sources at various positions in a phantom with shape and photon attenuation characteristics similar to the human body are shown in Fig. 5 for three counting geometries.

It is interesting to estimate the effect of movement of the source in the dorso-ventral direction for the three geometries with a subject 20 cm

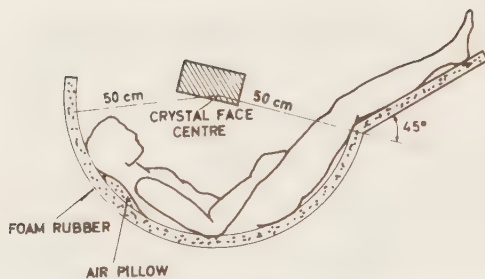


FIG. 4. Schematic representation of the crystal-subject arrangement in the 50-cm arc chair [34]

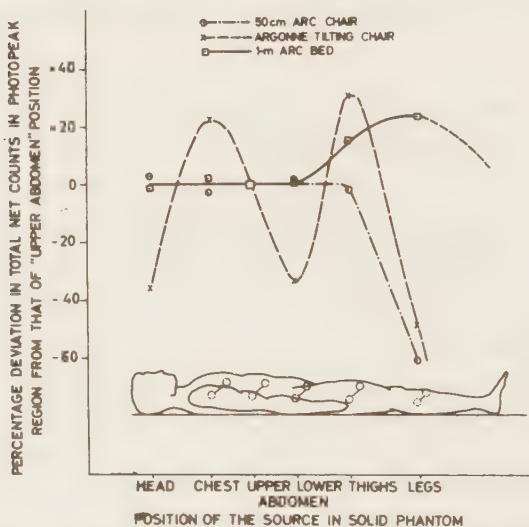


FIG. 5. Longitudinal response variation in three counting geometries: 1-m arc, 42-cm chair, 50-cm arc chair. A ^{137}Cs source has been measured at various places along the centre line of a solid Masonite phantom. Pulses in the photopeak energy band have been used. The curves show the percentage deviation from the response obtained in the lower abdomen region [34]

thick. In the 1-m arc the source is moved radially from the distance of 80 cm to 100 cm; in the 50-cm arc chair the source is moved from 30 to 50 cm; in the 42-cm chair from 22 to 42 cm. The geometrical effect is assumed to follow the "inverse square law". For comparison the response change due to the pure attenuation is also calculated for three total linear attenuation coefficients in water:

$$\begin{aligned}\mu &= 0.063 \text{ cm}^{-1} \text{ for } ^{47}\text{Ca} (1.31 \text{ MeV}) \\ \mu &= 0.086 \text{ cm}^{-1} \text{ for } ^{137}\text{Cs} (0.66 \text{ MeV}) \\ \mu &= 0.160 \text{ cm}^{-1} \text{ for } ^{57}\text{Co} (0.12 \text{ MeV})\end{aligned}$$

TABLE II

THEORETICALLY ESTIMATED RESPONSE VARIATION OF
THREE WHOLE-BODY COUNTING GEOMETRIES

The attenuation effect is calculated for three total linear
attenuation coefficients for a point source
at different depths in a phantom

Depth	Geometrical effect (inv. sq. law)			Attenuation effect		
	1-m arc	50-cm arc chair	42-cm chair	$\mu = 0.063$ cm^{-1}	$\mu = 0.086$ cm^{-1}	$\mu = 0.160$ cm^{-1}
0	1.00	1.00	1.00	1.00	1.00	1.00
5	0.88	0.73	0.66	0.73	0.65	0.45
10	0.79	0.56	0.47	0.53	0.42	0.20
15	0.71	0.45	0.35	0.39	0.28	0.091
20	0.64	0.36	0.27	0.28	0.18	0.041

It should be noted that experimentally with a narrow photopeak energy band somewhat smaller attenuation coefficients are obtained, and if also or only a Compton energy band is used the attenuation effects may be further diminished. However, the results of Table II grossly represent the situation. All values are normalized to unity at the anterior surface of the subject. It is evident that the counting efficiency of nuclides in the body is largely dependent on the dorso-ventral position of the radioactive source. In particular the chair techniques are not useful for clinical whole-body assay of γ - or X-ray emitters of rather low photon energy.

In geometries where the patient can be measured in both a PA and an AP position (or with equivalent counting arrangement) the situation is much more favourable. Thus, if a subject, 20 cm thick, is measured with the 1-m arc technique in a PA and an AP position, the central point source of the three nuclides mentioned will be counted with roughly 40%, 70% and 80% efficiency respectively, compared with 100% for point sources on the ventral and dorsal surfaces of the subject. This is a tremendous improvement compared with a one-side measurement, 1-m arc technique with a response at the distal surface of the subject amounting only to 2%, 11% and 17% for the same nuclides. With chair techniques the response at the distal surface is likely to be even worse.

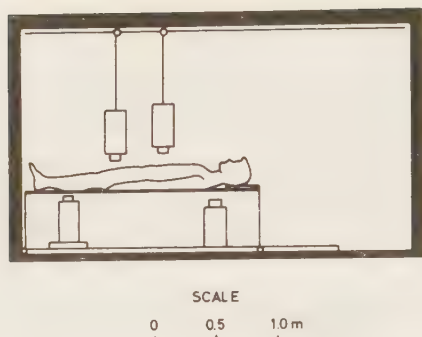


FIG. 6. Schematic representation of RUNDO's bed geometry with four fixed detectors [177]

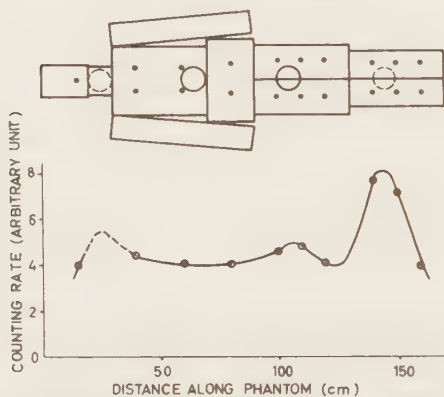


FIG. 7. The longitudinal response variation of the counting geometry shown in Fig. 6. The curve represents the results of measurement of a pair of point sources at various positions inside the phantom [177]

THE BED GEOMETRY WITH AN ARRAY OF FIXED DETECTORS

Several attempts have been made to eliminate the effects of inhomogeneous and dynamic radioactivity distributions in the body by spreading out several detectors along the human body [33, 89, 136, 139, 144, 177]. Rundo [177] has reported a counter with the patient lying on a stretcher, two detectors being suspended above the patient and two detectors below the stretcher. The crystals were arranged in such a way as to minimize the response variations from a unit mass of potassium in bodies of varying shape, weight and height (Fig. 6). The detectors under the stretcher were 120 cm apart, while those above were 40 cm from each other. The detectors near the head end were placed further from the stretcher than the detectors above and below the legs. The response variation was investigated with a pair of point sources in various positions along a phantom of roughly human shape and density. The response is fairly independent of

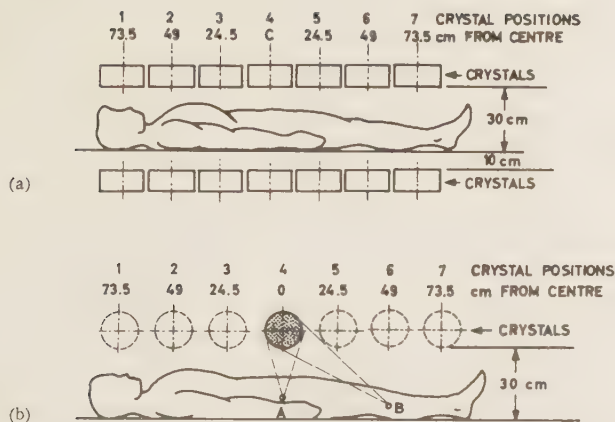


FIG. 8. Schematic representation of the crystal positions relative to the body in the single crystal, multiple position technique.

(a) Crystal axis vertical [136].

(b) Crystal axis horizontal [139]

the source position along the body except for the lower legs, where the count-rate per emitted γ -ray was almost 100% higher (Fig. 7). This artifact probably is of minor importance in the assay of ^{137}Cs and of potassium in the body. However, for measurements of ^{85}Sr and ^{47}Ca in clinical applications it might produce undesired effects, for instance in cases of localized pathologically high uptake in the legs.

A single crystal, multiple position technique with one 8 in. $\times$ 4 in. NaI(Tl) crystal in seven equidistant positions above and below the stretcher (Fig. 8a), has been reported [136]. This technique was later improved by the use of a NaI(Tl) crystal, 15 cm in diameter and 20 cm long [139]. The unique point is that the crystal is suspended with the axis horizontal and transverse with respect to the long axis of the recumbent patient. (Fig. 8b). The one-crystal, multiple position technique can give valuable information on the body activity distribution [89, 136, 138, 139]. The response of body potassium was dependent on the ratio weight-to-height when the patients were measured with the single-crystal, multiple position technique as well as when they were measured with the standard chair technique. This is mainly caused by attenuation of photons traversing the human body. For correction of the counter response for various body builds the body thickness should be used as a parameter, that is $(wt/ht)^{1/2}$ rather than weight, height or weight/height.

A low-level whole-body counter consisting of 8 NaI(Tl) crystals, arranged in two symmetrical arrays of detectors, one above and one below the horizontal patient, has been described [144] (Fig. 9). The longitudinal response variation, shown at the top of Fig. 9, was obtained by measurement in air of a point source of ^{137}Cs placed at 20-cm intervals along the midline of the counting space. The extremely low response variation along this line in air together with the fact that the detectors are positioned at an unusually long distance from the subject make it

geneously distributed in a volume V the average GF_V may be defined by Eq.1.

$$GF_V = \frac{1}{V} \int_V GF(x, y, z) dV \quad (1)$$

where $GF(x, y, z)$ is the GF of the volume dV with the co-ordinates (x, y, z) .

For a point source and a fixed detector of negligible size the ideal GF would be inversely proportional to the square of the distance between the detector and the source. In practice, the detector may often be thought of as existing at a point almost satisfying the inverse square law.

Particularly good conditions would exist for the scanning bed whole-body counter if IE were independent of the direction of the incident photons and if the GF were the same for all points at a constant distance from a certain point within the detector, i.e. for isotropic IE and GF characteristic of the detector. In practice neither IE nor GF are absolutely isotropic. However, these parameters could be matched in such a way that the product $IE \times GF$ is quite constant for all points at the same distance from a central point (inside or outside) the detector. The position of this point may vary with the energy of the incident photons. A NaI(Tl) crystal, 12.5 cm in diam. and 10.0 cm thick, may be used in such a way that $IE \times GF$ is fairly isotropic in a valuable angle interval when this detector is used in a scanning bed geometry [147].

The GF_{Sc} of a scanning detector geometry could be defined as that fraction of the solid angle 4π that is subtended by the detector during one scan, as seen from a point source, just as the GF could be defined for a detector slab of the same length as the scan [59]. For a point source measured with a detector scan, depending on the geometrical parameters, the GF_{Sc} follows a law somewhere between h^{-1} and h^{-2} , where h is the distance from the source to the linear detector orbit.

Isotropic detectors in general will be considered, and therefore IE and GF_{Sc} will not be discussed separately. For a point source when IE and GF_{Sc} are pooled the geometrical efficiency (G_{eff}) of the detector scan may be defined as the counting efficiency of an ideal point source where any attenuation between the source and the detector is ignored [147]. Thus for a point source

$$G_{eff} = \text{constant} \times \frac{\text{number of pulses obtained during the scanning time}}{\text{number of photons emitted during the scanning time}}$$

Analogously to Eq.1 for the volume V we have the average $G_{eff, V}$.

$$G_{eff, V} = \frac{1}{V} \int_V G_{eff}(x, y, z) dV \quad (2)$$

where $G_{eff}(x, y, z)$ is the G_{eff} of the volume dV with the co-ordinates (x, y, z) .

The number of pulses per scan (N) obtained may be derived [147] as

$$N = C_1 \times \frac{t}{a \times h} \times \int_{-a}^{+a} \frac{h \times du}{h^2 + (c-u)^2} = C_1 \times \frac{t}{a \times h} \int_{\phi_1}^{\phi_2} d\phi = C_1 \times \frac{t}{a \times h} (\phi_2 - \phi_1) \quad (3)$$

where h is the distance between the point source and the scanning orbit of length 2a (Fig. 10),

$(\phi_2 - \phi_1)$ is the angle between the lines of aim to the end points of the scanning orbit,

c is the position of the source from the centre on a line parallel to the scanning orbit,

u is the momentary detector position from centre of orbit,

t is the scanning time and C_1 is a constant.

From Eq. 3 and the definition of G_{eff} we realize that G_{eff} may be described by the function

$$G_{\text{eff}}(\phi, h, a) = C_2 \times (\phi_2 - \phi_1) / ah \quad (4)$$

where C_2 is a constant.

The response to distributed sources

The number of pulses (N) obtained when a radioactive volume V is measured with one scanning detector D (Fig. 11), scanning at a constant speed in a linear orbit, can be calculated as follows:

$$N = \int_V \int_{u=-a}^{+a} C_3(x, y, z, u) \times \frac{S(x, y, z) \times dx \times dy \times dz \times dt}{l^2} \times e^{-\mu \times f(x, y, z, u)} \quad (5)$$

$$\left\{ dt = \frac{du}{v}, \quad dV = dx \times dy \times dz \right\}$$

where 2a = length of orbit

t = measuring time

v = scanning speed

l = momentary distance from dV to detector

u = momentary detector position ($\pm$ from centre of orbit)

C_3 = "constant"

S = concentration (activity per unit volume)

μ = linear attenuation coefficient

f = momentary attenuation path length.

The calculus is made for isotropic detectors, i.e. C_3 is independent of the relative position of dV and the detector. Furthermore, S is constant

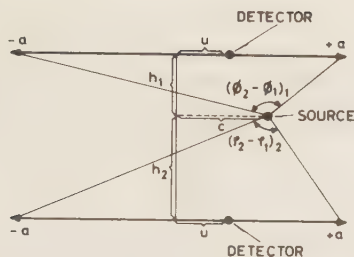


FIG. 10. Geometry of a point source in relation to two detector orbits

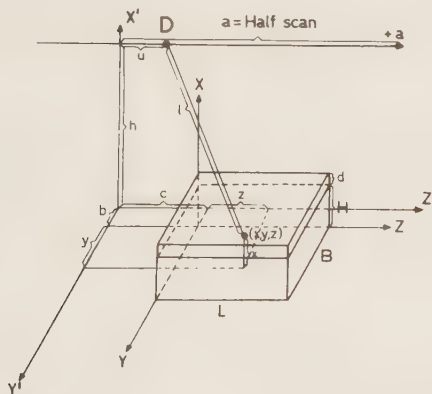


FIG. 11. Co-ordinate system with one scanning detector, D, and a parallelepiped radioactive volume

within the volume considered, since the activity distribution there is assumed to be homogeneous.

To get an estimate of geometrical effects as well as of attenuation effects in human beings when measured with scanning geometries, Eq. 5 was evaluated for a volume of 1 cm³ of radioactive material moved in the same non-radioactive material extended in such a way as not to require correction for margin effects [147].

When dealing with point sources the term efficiency is a function of the detector orbit length (2a) and the position of the point in relation to the orbit. The point position is defined by b and the previously mentioned parameters h and c. If h and c are fixed, b describes a line perpendicular to the detector orbit as well as to the distance vector from point h to the orbit. The efficiency variation will be described by the following functions:

(1) $G_{\text{eff}}(h)_{b=\text{const}} = \text{the vertical efficiency variation}$

$c = \text{const}$

(2) $G_{\text{eff}}(c)_{b=\text{const}} = \text{the longitudinal efficiency variation}$

$h = \text{const}$

(3) $G_{\text{eff}}(b)_{c=\text{const}} = \text{the lateral efficiency variation}$

$h = \text{const}$

For convenience the subscripts indicating that two of the three parameters are fixed will be omitted unless necessary for clarity. $G_{\text{eff}}(b)$ is of minor importance in the selection of parameters for optimal counting of human beings with one- and two-detector scans, and will therefore not be dealt with. When dealing with $G_{\text{eff}}(h)$ and $G_{\text{eff}}(c)$ b is always = 0.

Geometrical and attenuation parameters

In the following sections the response is evaluated for a point source in different positions in relation to different linear scanning detector orbits. In general points within a parallelepiped volume (called phantom), 20 cm thick, lying at a distance from, and parallel to, the orbit is considered. For two-detector scans it is assumed that the orbits are symmetrically situated on opposite sides of the phantom. It is also assumed that both orbits are of equal length.

The evaluation is performed for the following assumed situations:

- (1) The orbit lengths 150 cm, 200 cm or 300 cm.
- (2) The phantom situated 15 cm, 25 cm or 35 cm from the orbit(s).
- (3) In the case of two-detector scans, the distance between the orbits, since the phantom is 20 cm thick, is thus 50 cm, 70 cm or 90 cm.
- (4) Within the phantom the point source is displaced perpendicularly to the orbit(s).
- (5) Within the phantom the point source is displaced parallel to the orbit(s).
- (6) Besides $\mu = 0$, the following total linear attenuation coefficients are assumed: 0.063, 0.078, 0.086, 0.095, 0.110 and 0.160 cm^{-1} .

If no attenuation is considered, i.e. $\mu = 0$, the G_{eff} is obtained.

The μ -values from 0.063 to 0.160 cm^{-1} correspond to the total attenuation in water of photons of ^{47}Ca (1.31 MeV), ^{65}Zn (1.11 MeV), ^{137}Cs (0.66 MeV), ^{85}Sr (0.51 MeV), ^{51}Cr (0.32 MeV) and ^{57}Co (0.12 MeV) [213].

Vertical geometrical efficiency

From Eq. 4 $G_{\text{eff}}(h)_{c=0}$ (the central vertical efficiency) apart from the factor C_2 was calculated for different values of h (Fig. 11). The results for $2a = 150$ cm as well as for $2a = 300$ cm are shown in Table III. Columns 2 and 5 show how $(\phi_2 - \phi_1)/h$ varies with h . This correlation is plotted in a log-log diagram in Fig. 12. We find that the $G_{\text{eff}}(h)$ for small h up to about 10 cm varies roughly as h^{-1} , and for $h = 100$ cm roughly as $h^{-3/2}$. In practice, h -values from, say, 10 cm to 50 cm, will probably be most frequently used. In this region the $G_{\text{eff}}(h)$ in the central vertical of a one-detector orbit varies roughly as $h^{-5/4}$ for $2a = 150$ cm and roughly as $h^{-8/7}$ for $2a = 300$ cm. If the distance between two scanning orbits is 70 cm, G_{eff} in the central vertical of a 20-cm thick phantom in the case of $2a = 150$ cm will vary by 12% and in the case of $2a = 300$ cm by 10%. If the distance between the scanning orbits is only 50 cm, the same variations would be 22% and 19% respectively. These figures are in fairly good agreement with what could be calculated from columns 2 and 5 in Table III. This rough estimation indicates that the change of the vertical G_{eff} is of

TABLE III

THE RELATIVE GEOMETRICAL COUNTING EFFICIENCY
 ACCORDING TO EQ.(4) AND EXPERIMENT AT DIFFERENT LEVELS
 OF ONE-DETECTOR SCANS, 150 cm LONG (a = 75 cm)
 AND 300 cm LONG (a = 150 cm)

The values in columns 3, 4, 6 and 7 are normalized to unity for h = 25 cm, which corresponds to the upper surface of a patient, 20 cm thick, measured in such a way that the distance between detector and the bed is 45 cm. Two symmetrical scans would correspond to a two-detector scan with an orbital distance of 70 cm. The last column shows the average efficiency in the central vertical of the 300-cm scan compared with the average efficiency of the 150-cm scan. For the experimental results with ^{137}Cs the distance is measured to a point 5 cm inside the crystal on the axis of the crystal.

h	2a = 150 cm			2a = 300 cm			[[$(\phi_2 - \phi_1)/ah$]] _{2a = 300 cm}	
	$\phi_2 - \phi_1$ a x h	Normalized		$\phi_2 - \phi_1$ a x h	Normalized		[[$(\phi_2 - \phi_1)/ah$]] _{2a = 150 cm}	
		theor.	exper.		theor.	exper.	Theor.	Exper.
		Eq. 4			Eq. 4			
5	0.4596	6.021		0.2349	5.471		0.51	
10	0.2198	2.879		0.1149	2.676		0.52	
15	0.1399	1.837		0.07493	1.745		0.54	
20	0.1001	1.311	1.29	0.05493	1.279	1.29	0.55	0.53
25	0.07633	1.000	1.00	0.04295	1.000	1.00	0.56	0.53
30	0.06063	0.794	0.83	0.03497	0.814	0.79	0.58	0.53
35	0.04951	0.649	0.67	0.02929	0.682	0.69	0.59	0.56
40	0.04128	0.541	0.57	0.02503	0.583	0.61	0.61	0.60
45	0.03499	0.458	0.48	0.02172	0.506	0.51	0.62	0.61
50	0.03003	0.393	0.41	0.01909	0.445	0.46	0.64	0.59
55	0.02605	0.341	0.36	0.01694	0.395	0.41	0.65	0.57
60	0.02281	0.299		0.01511	0.352		0.66	
65	0.02013	0.264		0.01365	0.318		0.68	
70	0.01789	0.234		0.01238	0.288		0.69	
75	0.01600	0.210		0.01127	0.262		0.70	
80	0.01439	0.189		0.01032	0.240		0.72	
85	0.01300	0.170		0.009480	0.221		0.73	
90	0.01179	0.154		0.008747	0.204		0.74	
95	0.01075	0.141		0.008087	0.188		0.75	
100	0.00983	0.129		0.007507	0.175		0.76	

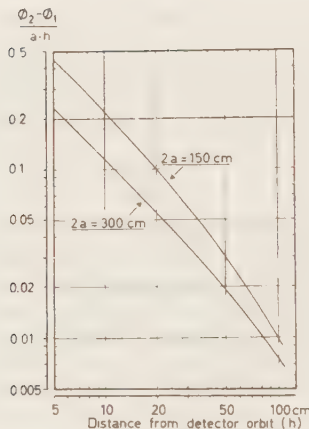


FIG. 12. The geometrical efficiency (apart from a constant) of a point source, as a function of the distance between the detector orbit and the source. The source is displaced in the central vertical ($c = 0$) or detector orbits, 150 cm and 300 cm long

minor importance in the selection of the length of orbit. However, they indicate that the measuring accuracy increases with the distance between the scanning orbits.

Weak small sources of ^{137}Cs encapsulated in perspex were measured at several positions in relation to the scanning orbit if a NaI(Tl) crystal (12.5 cm in diam. by 10.0 cm thick). The distance h was measured from the source to the front surface of the crystal.

Table IV shows the results of measurements of a source at different distances below the middle of a scan, 150 cm long, and the corresponding results when the source was measured at the end of the same scan. In column 4 the net count-rates (N/t) are related to $(\phi_2 - \phi_1)/h$ of Eq. 4 with appropriate values of angles and distances. If the experimental results were in agreement with Eq. 4, this ratio should be independent of h . In column 5 the count-rates are also related to $(\phi_2 - \phi_1)/h$; however, the distance h is here referred to a point within the crystal, on the axis, 5 cm from the frontal surface. In this case the experimental results agree very closely with what could be expected from Eq. 4. The same experimental data are also used in Table III, columns 4, 7 and 9, and in Table V, columns 4 and 7.

In Table III the vertical G_{eff} for one-detector scans could be seen for h -values from 5 cm to 100 cm (columns 2 to 7) as well as the efficiency of a 300-cm scan compared with the efficiency of a 150-cm scan (columns 8 and 9). These should be compared with the columns in Table V. The longer scan is thus roughly only 60% as effective as the shorter one, i.e. if a point source is positioned in the centre between the two orbits of a 300-cm scan less than 20% more pulses will be obtained than if a 150-cm scan is used.

The data given in Table III can be used to estimate the vertical efficiency of two-detector scans. Table V shows results for a two-detector

TABLE IV

COMPARISON OF THEORETICAL EXPECTED AND EXPERIMENTAL OBTAINED VARIATION OF VERTICAL GEOMETRICAL EFFICIENCY

Point source: $(0.094 \pm 0.002) \mu\text{Ci } ^{137}\text{Cs}$; energy range: 600 to 720 keV;
uncertainty indicated by 2 S.D.

Geometry parameters: $2a = 150 \text{ cm}$; $b = c = 0$

h	$(\phi_2 - \phi_1)_{a,h}$	Net counting rate (N/t) counts/min	$\frac{N}{t} \times \frac{h}{(\phi_2 - \phi_1)_{a,h}}$	$\frac{N}{t} \times \frac{(h+5)}{(\phi_2 - \phi_1)_{a,h+5}}$
15	157.38°	971.9 ± 28.4	92.6 ± 2.8	129.5 ± 3.8
20	150.14°	755.9 ± 25.2	100.7 ± 3.4	132.0 ± 4.4
25	143.12°	625.1 ± 23.0	109.2 ± 4.0	137.5 ± 5.1
30	136.40°	508.3 ± 20.9	111.8 ± 4.6	136.9 ± 5.6
35	129.96°	430.5 ± 19.4	115.9 ± 5.2	139.1 ± 6.3
40	123.84°	363.5 ± 18.2	117.4 ± 5.9	138.6 ± 6.9
45	118.06°	311.9 ± 16.8	118.9 ± 6.4	138.5 ± 7.5
50	112.62°	269.9 ± 15.6	119.8 ± 6.9	138.1 ± 8.0
55	107.49°	-	-	-

Geometry parameters: $2a = 150 \text{ cm}$; $b = 0$; $c = 75 \text{ cm}$

15	84.29°	526.0 ± 21.2	93.6 ± 3.8	127.7 ± 5.1
20	82.40°	407.4 ± 18.3	98.9 ± 4.4	126.5 ± 5.7
25	80.54°	323.7 ± 16.9	100.5 ± 5.2	123.4 ± 6.4
30	78.69°	280.9 ± 15.9	107.1 ± 6.1	127.9 ± 7.2
35	76.87°	246.5 ± 15.1	112.2 ± 6.9	131.3 ± 8.0
40	75.07°	209.3 ± 14.1	111.5 ± 7.5	128.5 ± 8.7
45	73.30°	186.3 ± 13.4	114.4 ± 8.2	130.1 ± 9.4
50	71.57°	165.3 ± 12.8	115.5 ± 8.9	130.1 ± 10.1
55	69.88°	-	-	-

TABLE V

THE RELATIVE GEOMETRICAL COUNTING EFFICIENCY, ACCORDING TO EQ. (4) AND EXPERIMENT OF DIFFERENT LEVELS OF TWO-DETECTOR SCANS, 150 cm LONG AND 300 cm LONG

The distance between the detector orbits is 70 cm.

The values in columns 3, 4, 6 and 7 are normalized to unity at the level of the surface of a "subject", 20 cm thick, exactly intermediate between two parallel detector scans.

For the experimental results with ^{137}Cs the level is related to a point 5 cm inside the crystal on the axis of the crystal.

"h ₁ + h ₂ "	2a = 150 cm				2a = 300 cm				[(φ ₂ - φ ₁)/ah] _{2a = 300 cm} [(φ ₂ - φ ₁)/ah] _{2a = 150 cm}
	$\frac{\phi_2 - \phi_1}{a \times h}$	Normalized		$\frac{\phi_2 - \phi_1}{a \times h}$	Normalized				
		theor. Eq. (4)	exper.		theor. Eq. (4)	exper.			
20 + 50	0.1302	1.168	1.15	0.0741	1.146	1.15	0.57		
25 + 45	0.1115	1.000	1.00	0.0647	1.000	1.00	0.58		
30 + 40	0.1020	0.915	0.94	0.0599	0.926	0.92	0.59		
35 + 35	0.0992	0.890	0.91	0.0587	0.908	0.91	0.59		

scan when the orbital distance was 70 cm. When comparing the data in Table III and V the better "homogeneity" in Table V is quite evident.

Vertical efficiency variation with scanning length and with distance from detector orbit to phantom surface

To estimate the G_{eff} when more than one parameter is changed, data were obtained from automatic data treatment of Eq.5. Thus G_{eff} was obtained when $\mu = 0$ was substituted. The evaluation was made for 1-cm³ cubes displaced in the central vertical ($c = 0$) from 15 cm to 55 cm from the orbit, which was either 150 cm, 200 cm or 300 cm long. The results are given in Fig.13a, b, c.

Fig.13a shows the G_{eff} in the central vertical for a scanning length of 150 cm and a distance 25 cm from detector orbit to upper surface of phantom. Thus the range of h from 25 to 45 cm corresponds to a depth of 0 to 20 cm in the phantom. The results in Fig.13a agree well with the laws deduced above. For instance, supposing a variation with $h^{-5/4}$ (Fig.12), a movement of the source from $h = 25$ cm to $h = 45$ cm below the centre of a 150 cm scan should correspond to a decrease in the obtained number of pulses to 48%, which compares well with the result of 46% in Fig.13a.

Fig.13b shows G_{eff} as a function of scanning length. It can be seen that $G_{\text{eff}}(h)$ within 10% is independent of the length of the detector orbit, when the length is doubled from 150 to 300 cm. Thus 2a can be selected independently within this range without any remarkable change in the G_{eff} with depth in the phantom. However, the sensitivity decreases considerably with increase in length of the orbit. This is apparent from the relative efficiencies at the arrows in Fig.13b. Depending on the depth in the phantom a 200-cm scan was 80 to 82%, and a 300-cm scan was 56 to 62% as effective as the 150-cm scan.

Fig 13c shows how G_{eff} can be expected to change when the vertical distance from the detector orbit to the upper surface of the phantom is varied from 25 cm to 15 cm or 35 cm. This is here calculated for $2a = 150$ cm. An important improvement of the characteristic of the vertical G_{eff} is obtained when the distance is increased from 15 to 35 cm.

Longitudinal geometrical efficiency

The variation of G_{eff} as a function of the longitudinal co-ordinate c of the point source will be confined to a range of c from -110 cm to +110 cm from the central vertical. Due to the symmetry around this line, only points covered by the positive half scan will be discussed. The evaluation of Eq.5 (for $\mu = 0$) was made for 1-cm³ cubes moved 10 cm at a time along lines at different distances from the orbit of one scanning detector.

Fig.14a, b, c show the $G_{\text{eff}}(c)$ for $2a = 150$ cm, $2a = 200$ cm and $2a = 300$ cm respectively. The efficiency is normalized to 1 when the source is in the position $c = 0$. To take into account the vertical efficiency variation, as discussed earlier, $G_{\text{eff}}(h)$ is given as "Rel. eff. at centre" in the tables inserted in Fig.14a, b, c.

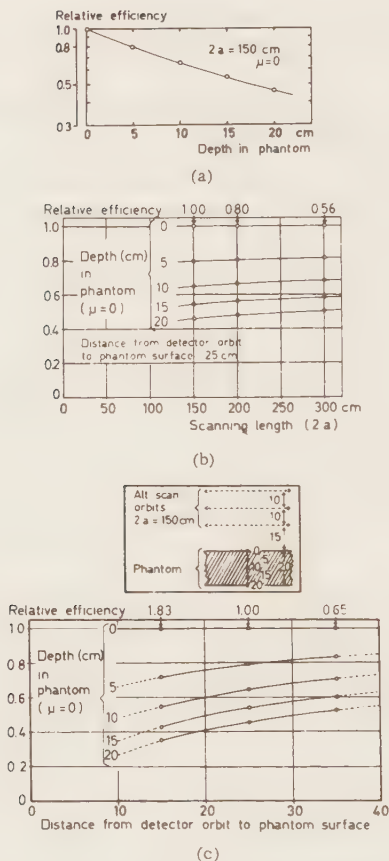
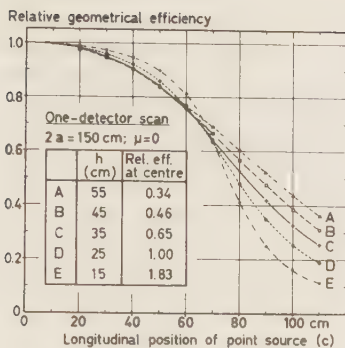
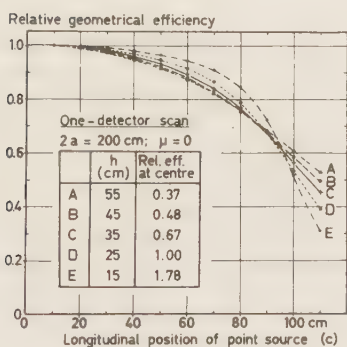


FIG. 13. The geometrical efficiency for one-detector scans at different depths in a phantom 20-cm thick.
 (a) Orbital length: $2a = 150$ cm. The depth range corresponds to h -values from 25 to 45 cm.
 (b) Efficiency as a function of orbital length. The depth in the phantom corresponds to h -values from 25 to 45 cm.
 (c) Efficiency as a function of the distance to the phantom, which is 20-cm thick. The calculated values thus show the relative efficiency in the following ranges of h : 15 to 35 cm, 25 to 45 cm, and 35 to 55 cm.

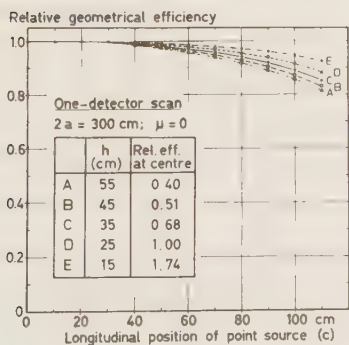
The point source is assumed to be situated in different positions (different c) at five different levels (different h), 15 cm, 25 cm, 35 cm, 45 cm and 55 cm from the scanning orbit. The S-shape of the curves obtained could be expected from considerations of the various angles ($\phi_2 - \phi_1$) of Eq. 4 corresponding to the different positions of the point. In an important range around the centre (c from 0 to about $0.9a$), a low h -value gives a less rapid variation of G_{eff} with c than does a large h -value. For points covered by peripheral parts of the orbit, however, the relative reduction is less for large h -values. That is, the S-shape of the curves is more pronounced for the lower h -values.



(a)



(b)



(c)

FIG. 14. The geometrical efficiency as a function of the longitudinal position (c) of the point source at different distances from the orbit of one-detector scans. The efficiency is normalized to unity for the source position $c = 0$. The relative efficiencies on the different levels may be taken into account by use of the values given as the "Rel. eff. at centre".

(a) Length of detector orbit = 150 cm

(b) Length of detector orbit = 200 cm

(c) Length of detector orbit = 300 cm

By comparing Fig. 14a, b, c it will be seen that a redistribution of sources in longitudinal direction will affect the count-rate more when a short orbit is used. If $2a = 150$ cm, a movement of the radioactive source from $c = 50$ cm to 90 cm could reduce the response to about 50%, and from the position $c = 10$ cm to 50 cm, the reduction is expected to be less than 20%. If $2a = 300$ cm, the reduction by the redistribution from $c = 0$ all the way to $c = 90$ cm should be less than 20%.

From the data obtained for only one scanning detector the $G_{\text{eff}}(c)$ can be calculated also for two-detector scans. It can be shown that the largest relative vertical variation will be found for c -values between zero and a and the least variations for c -values greater than a . For instance, for a two-detector scan, 150 cm long, at $c = 110$ cm the absolute G_{eff} is almost independent of the level of the source within the phantom.

Attenuation effects

For radioactive material distributed in large volumes such as the human body the response of the detectors is affected to a very large extent by the attenuation of the photons emitted in the volume itself. In fact the attenuation effect in general will be a more serious problem than the geometrical effect. For scanning geometries and similar quasi- 4π geometries the attenuation effect is particularly a problem of what is here called the vertical efficiency variation.

Fig. 15 shows the calculated pure attenuation effect on the efficiency of point sources at different levels in a water phantom using one detector, scanning 150 cm at a distance 25 cm from the phantom. From a comparison with Fig. 13a it can be seen that the effect of attenuation is much greater than that of the geometry. Fig. 16a and 16b show that roughly the same results are obtained for other lengths of the scanning orbit and other distances between the detector orbit and the phantom.

For a two-detector geometry, the calculated total vertical efficiency variation is shown in Fig. 17 as a function of vertical position of source in a 20-cm thick phantom. It is calculated for two symmetrical orbits, 150 cm long, with an orbital distance of 70 cm, for six attenuation coefficients as well as for $\mu = 0$. We see that the G_{eff} is of minor importance for the total efficiency variation. In the middle of a water phantom, 20 cm thick, the total efficiency for a source of ^{47}Ca is only 50%, and for ^{57}Co only 20% of the efficiency at either surface.

For minimizing the effect of vertical redistributions in recumbent human beings the choice of orbital length and orbital distance in the ranges considered is not very critical. However, the combination of a long orbital length and (therefore probably) a short orbital distance will be least favourable.

A point source of ^{137}Cs was measured at different depths in a Masonite phantom (thickness 20 cm, average weight 0.92 g/cm^3) below the centre of the scanning detector. The number of counts in different energy ranges was calculated. From these data the vertical efficiency variation compatible with a symmetric two-detector scan was deduced. The distance between the detector orbits was assumed as 70 cm. The result is

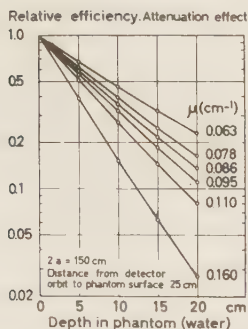
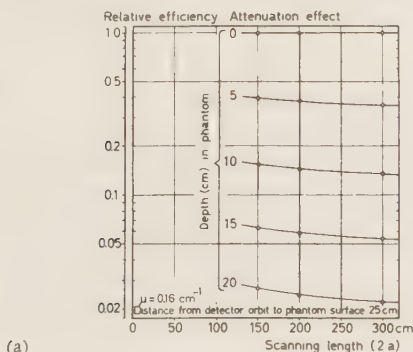
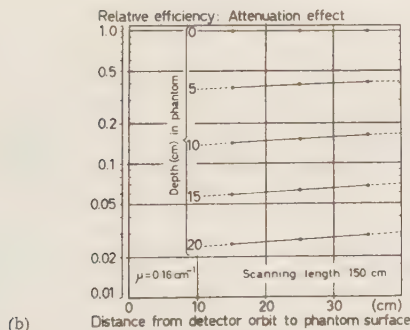


FIG. 15. The pure attenuation effect as a function of point source depth in water



(a)



(b)

FIG. 16 (a) The pure attenuation effect for $\mu = 0.160 \text{ cm}^{-1}$ as a function of the length of orbit.

(b) The pure attenuation effect for $\mu = 0.160 \text{ cm}^{-1}$ as a function of distance from the detector orbit to the phantom

shown in Fig. 18. Using counts in the photopeak area a rather good agreement with the theoretically calculated curve was obtained.

On the other hand, if only the Compton region for ^{137}Cs , say 250 keV to 500 keV, were used, a response almost independent of the vertical site of the activity would be obtained.

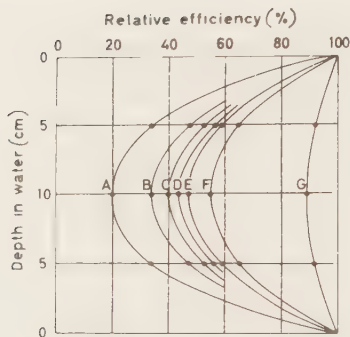


FIG. 17. The total efficiency variation of both geometry and attenuation effects of a two-detector scan, 150-cm long, as a function of vertical position of a source in the phantom 20 cm thick. The distance between the orbits, situated symmetrically on either side of the phantom, is 70 cm. The efficiency is calculated for following μ -values (cm^{-1}): A: 0.160, B: 0.110, C: 0.095, D: 0.086, E: 0.078, F: 0.063 and G: $\mu = 0$

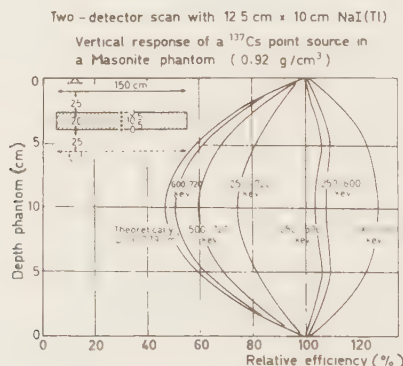


FIG. 18. Vertical response variation of a ^{137}Cs point source in a Masonite phantom at the centre of a two-detector scan. The experimental curves indicated by different energy ranges are deduced from measurements scanning with one 12.5-cm $\times$ 10-cm NaI(Tl) crystal. The first curve to the left is the theoretically calculated response variation

The total longitudinal efficiency variation for three orbit lengths, $2a$, and for four μ -values is shown in Fig. 19 for a two-detector scan. An orbital distance of 70 cm and movement of the source in the middle of a water phantom, placed exactly between the orbits, is assumed. The relative efficiency is unity when the source is in the position $c = 0$ for each value of $2a$. Fig. 19 shows that oblique photon penetration of the phantom results in a further depression of the efficiency of counting sources outside the ends of the orbits. On the other hand, the attenuation causes a collimation effect, so that relatively more pulses are obtained when the detector is momentarily above the source. Therefore, beyond the points of inflexion, the curves for $\mu = 0$ lie above the curves for $\mu \neq 0$.

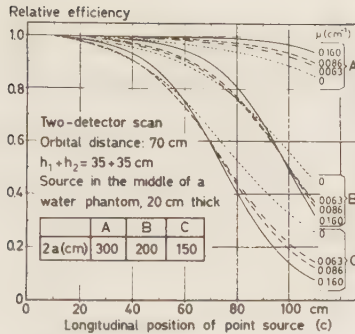


FIG.19. The total efficiency variation of two-detector scans (orbital length: (A) $2a = 300$ cm, (B) $2a = 200$ cm and (C) $2a = 150$ cm) as a function of longitudinal position (c) of point source in the middle of a water phantom, 20 cm thick, for $\mu = 0$, $\mu = 0.063$ cm⁻¹, $\mu = 0.086$ cm⁻¹ and $\mu = 0.160$ cm⁻¹

CONCLUSION

Investigations regarding the scanning bed geometry show that if the sum of the pulses in the photopeak energy range obtained during a two-detector scan is used for the assessment of body activities, independently of the counter parameters there will be effects of vertical redistributions. Longitudinal redistributions may be largely eliminated by the use of scanning orbit lengths longer than the patient. However, in such a case the absolute efficiency will go down remarkably.

DISCUSSION

A. BEN HAIM: Did you attempt to verify the attenuation curves experimentally? I understand that these figures were obtained from theoretical calculations using attenuation coefficients from the tables of Gladys White. I think that if you do the experiments you will find that the attenuation coefficients are considerably lower than the theoretical values because you always introduce some scattered counts into your photopeak.

Y. NAVERSTEN: First of all, I would like to stress that the purpose of my paper is to show the inherent possibilities with the scanning bed geometry. Because of the evident difficulties with non-standardized shapes of human beings I have chosen to work as much as possible from a theoretical point of view and I have therefore also used published data on attenuation coefficients. Secondly, it is quite evident that with NaI(Tl) γ -ray spectrometry you generally measure smaller "attenuation coefficients" than published attenuation coefficients. The discrepancy is largely dependent on what part of the spectrum you use. In a previous discussion I showed Fig.18 of my paper with the experimentally obtained response for a point source of ¹³⁷Cs at various depths in Masonite. The data presented were a result of measured "attenuation" curves for the

different energy regions. When the 600-720 keV photopeak region was used a rather good agreement between experiment and theory was observed.

A. BEN HAIM: Have you averaged out the effect of attenuation by taking out the conjugate?

Y. NAVERSTEN: Yes, I used the arithmetic mean of the response of conjugate points, in the same way as Mr. Genna.

E. OBERHAUSEN: I have a question about the variation of sensitivity along the longitudinal axis in the scanning bed geometry. Do I understand that you found a drop in sensitivity of about 50% at the end of your scanning length?

Y. NAVERSTEN: Yes, for point sources positioned below the ends of the scanning orbit we can expect about 50-60% as many pulses as if the point source was positioned below the centre of the scanning orbit. The exact fraction depends on the length of the scanning orbit and the distance between the source and the orbit.

E. OBERHAUSEN: We have about the same loss in sensitivity and we are not pleased with this variation at the ends. To correct for this variation we varied the speed of the scanning crystals and shortened the scan length. In this way it was possible to achieve a system with a scan length of 170 cm, which has a variation of only 5%.

H.I. GLASS: Where do you start changing the speed?

E. OBERHAUSEN: All the time.

H.I. GLASS: You need negligible change of speed for 70 or 80% of the scan, because the sensitivity is 100% over most parts and drops off only at the end of the scan. Would it not be better to use an end pause method, i.e. just stop the counter for a period at the end of the scan?

E. OBERHAUSEN: Yes, but we found that mathematically you cannot reach the final gain merely by stopping the detector.

H.I. GLASS: Worthley in Australia uses this end-stop method and gets very good results. He stops for about $1\frac{1}{2}$ min at the end of each scan and his results are $\pm 2\%$ over the whole length. At Cambridge they also use an end-stop method. I think they started with profiling the speed, but this was abandoned.

Y. NAVERSTEN: I think this is a matter of how much money you have. Alternatively, you would obtain a rather constant longitudinal efficiency with stops at the ends plus a number of stops during the scan.

H.I. GLASS: Yes, this is possible: to stop for a short period and then for a longer period. While it is easy to programme stops, it is not easy to programme a gradual variation that you may have to vary for different isotopes.

P. REIZENSTEIN: It would be very valuable to get from the data presented by Naversten some idea of the actual magnitude of the error introduced by a change in isotope distribution. I do not refer to the "longitudinal error" or to the geometrical error due to a change in shape of the radiation source, but I refer only to the attenuation error. Let us assume a man with a thickness of 20 cm and with all the isotope (1 MeV) concentrated in the midline. If redistribution causes a change in activity to halfway to the surface, the "line of radioactive gravity" changes about 2 to 2.5 cm. Is my calculation of a change in efficiency of about 4%

correct and wouldn't the error be even smaller with an integral instead of a photopeak count?

Y. NAVERSTEN: My Fig.10 concerns a two-crystal arrangement. On your assumptions of a 20-cm thick patient and about 1-MeV photon energy a redistribution from the midline to 2.5 cm from the midline would result in an increase of the number of pulses of about 5%.

For large NaI(Tl) crystals and most clinically used nuclides a large fraction of the pulses in the whole spectrum are collected in the photopeak energy area, therefore the improvement by using an integral spectrum count is not the ultimate solution. The photopeak depth response for point ^{137}Cs sources in 20-cm water may vary from 100% at the upper and lower surfaces to about 50% at the middle. Integral counts above a lower discriminator at about 200 keV would decrease the envelope to about 100 to 75%.

H.I. GLASS: There is an optimum band to count for any particular isotope and you can select that band purely on spatial response from distributed sources.

P. REIZENSTEIN: There are, of course, many other advantages with using an integral count only. One is that it is extremely simple, and the other is that you gain a lot of efficiency.

Y. NAVERSTEN: Yes, you will roughly double your efficiency. It depends, of course, on both the detector and the photon energy.

A. BEN HAIM: I would like to go back to Fig.19, which deals with efficiency for point sources along the axis of the scan. When you increase your scanning length from 150 cm to 200 cm with a source position off centre of 100 cm, you have already reduced your discrepancy by about 40%. You went too far by taking a 300-cm scan as your next step. We find for a 235-cm scan with a source position at 100 cm there is a discrepancy of 16% for $\mu=0$.

Y. NAVERSTEN: This comment is probably correct since the relative efficiency drops very fast when the source is moved from 0.9a to 1.0a, where 2a is the length of scanning orbit. There are two reasons why I made the calculations for $2a = 300$ cm. People have asked me what happens for infinitely long scanning orbits. I therefore chose what I considered the absolute upper limit for a usable whole-body counter. Secondly, experimental work with point sources at the end of a 150-cm scan at the same time will check my theoretical calculations for points below the centre of a 300-cm scan.

A. BEN HAIM: How long is your room?

Y. NAVERSTEN: I can make a scan of 185 cm, and if I move the stretcher as well I can make it 250 cm.

J.G. MEHL: I have made some calculations using my slide rule and a number of assumptions. For example, we considered the body to be a line source and further assumed that the absorption for all radioisotopes is two thirds. Thus the body transmission rate is two thirds of the total radiation emitted in the body. With these crude assumptions and rough assessments of the geometrical factors, I have made a comparison of all the calibration data that were reported in the Directory of Whole-Body Monitors [128]. We wished to evaluate the reliability of those data re-

ported by the various investigators. It was surprising to see that one could by these simple calculations assess the measured data to an accuracy of $\pm 10\%$. This allowed me to sort out those data where errors must have been made. In many cases it became apparent that I got wrong geometrical data so that the calibration data reported did not refer in fact to the stated geometry. In other cases it appeared that there was something wrong with the standards used.

Y. NAVERSTEN: In reply to Mr. Mehl's comment regarding line sources, the data I have given in my paper, which only consider point sources, are only the first step. You may easily realize that, for instance, by integration below the curves of Fig. 19, one may obtain the results valid for line sources. My computer programme also permits me to calculate data for sources distributed in volumes. I have not directly considered volumes of the human shape. I have instead considered parallelepipeds in such a way that they can be added up to a phantom similar to the shape of human beings. In this way I hope I shall be able to predict something valuable about the efficiency variations that can be expected.

S. GENNA: What happens if you use the geometrical instead of the arithmetic mean?

Y. NAVERSTEN: I think that Mr. Dudley is going to talk about that in his paper and he is probably better prepared to comment upon that.

R.A. DUDLEY: The geometric mean has one mathematical advantage. If you are dealing with point sources whose absorption is exponential, the geometric mean will give a more reliable estimate of body burden than will the arithmetic mean. If you are dealing with a distributed source that is the common situation in clinical work you get about the same answer with the two methods.

S. GENNA: I think that there is a real, although very small, difference between using the geometric and arithmetic mean. The question may only be academic, since the difference in these quantities in most practical cases is negligible. Nevertheless, it is interesting to note that the geometric mean does give the more nearly correct answer, even for distributed sources. If we take Eqs. (3) and (4) in my paper, and combine them in terms of the geometric mean of the supine and prone count-rates, $(N_1 N_2)^{\frac{1}{2}}$, then the activity, as given in Eq. (5), is

$$S = \frac{(N_1 N_2)^{\frac{1}{2}}}{2\eta_0} \frac{\alpha}{\left[\sum_{i=1}^m \frac{C_i}{\mu_i} e^{\mu_i \gamma_0} \sinh \mu_i \alpha / 2 \sum \frac{C_i}{\mu_i} e^{-\mu_i \gamma_0} \sinh \mu_i \alpha / 2 \right]^{\frac{1}{2}}}$$

If, however, we had chosen to define S in terms of the arithmetic mean of the supine and prone counts, we would have

$$S = \frac{N_1 + N_2}{2\eta_0} \frac{\alpha}{\sum_{i=1}^m \frac{C_i}{\mu_i} e^{\mu_i y_0} \sinh \mu_i \alpha / 2 + \sum_{i=1}^m \frac{C_i}{\mu_i} e^{-\mu_i y_0} \sinh \mu_i \alpha / 2}$$

Both these equations contain two summations in the denominator. However, in the first equation these summations multiply each other while in the second they are additive. Since the first exponential term predominates in each summation, the dependence on y_0 is smaller in the first equation than in the second. Thus, the geometric mean gives more nearly the correct answer if the supine and prone counts differ from each other. However, the difference in the supine and prone count-rates must be large for the difference between the arithmetic mean and the geometric mean to be significant, i.e. y_0 , the centre of the radioisotope distribution must be large.

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SEMI-PORTABLE WHOLE-BODY COUNTER FOR
CESIUM 137 AND OTHER GAMMA-EMITTING ISOTOPES

by

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After the discovery of the unusually high ^{137}Cs burdens in Swedish Lapps (LIDÉN 1961) it was realized that a large group of people had to be studied to assess the actually existing contamination levels. Since the people to be measured were about 1 700 kilometers from the iron room whole-body counting facility (IRC) at Lund and since the Lapps are not easily available for long distance travelling, it was decided to design and construct a whole-body counter suitable for transport to Lapland.

The whole-body counter was designed around the following specifications.

1. It should be semi-portable, i.e. two men should be able to assemble or disassemble it for transport in a few hours.
2. It should have the same geometry as the 42 cm-chair arrangement in the stationary whole-body counter at Lund (CEDERQUIST & LIDÉN 1962).
3. The detector should be a 5'' in diam. by 4'' thick NaI(Tl) crystal.
4. Shielding must be presently available material, i.e. lead bricks; the amount of shielding must be minimized to facilitate transport.
5. It must be structurally safe.

It was expected that the Lapps would have ^{137}Cs body burdens in the range of $0.1 \mu\text{C } ^{137}\text{Cs}$ or more. With such a relatively large amount of activity it was not necessary to have a very low background. We were also of the opinion that

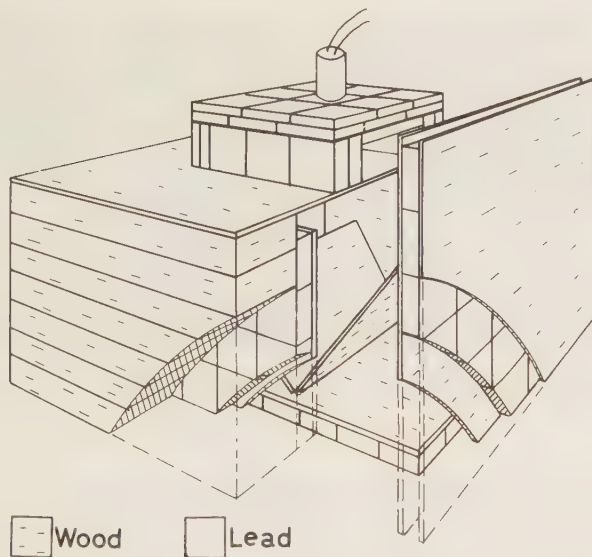


Fig. 1. Semi-portable whole-body counter. The shielding is supported by a structure of 8" $\times$ 4" timbers and plywood sheets.

determination of the body content of potassium was of a second order of importance.

There was very little experience to draw upon in the literature. ROESCH et coll. 1961, PALMER 1962 and LINDELL 1962 have done some work with simple shields.

Description of the whole-body counter. A stable basic structure of 8" $\times$ 4" timbers is made with a plywood roof (Fig. 1). A lead floor, 4 cm thick, is then laid. The wooden structure is used to support side walls of lead, 4 cm thick, with an inner retaining wall of plywood. A section of the plywood roof is cut out and replaced by a 4 mm lucite sheet in the area where γ -rays from the subject must pass to reach the detector. The detector, 5 inches in diameter and 4 inches thick NaI(Tl) crystal, rests upon this sheet of lucite. A small house of lead, the walls and roof of which are 8 cm thick, is built around three sides and above the top of the crystal. The fourth side must be open in order to let the γ -rays pass from the head and shoulders of the subject to the crystal. In order to strengthen the plywood roof, a 30 mm by 30 mm by 5 mm right angle iron beam is added at the head end of the plywood roof. A lead wall, 4 cm thick, held in position by two sheets of plywood, is built immediately behind the subject to close the open end.

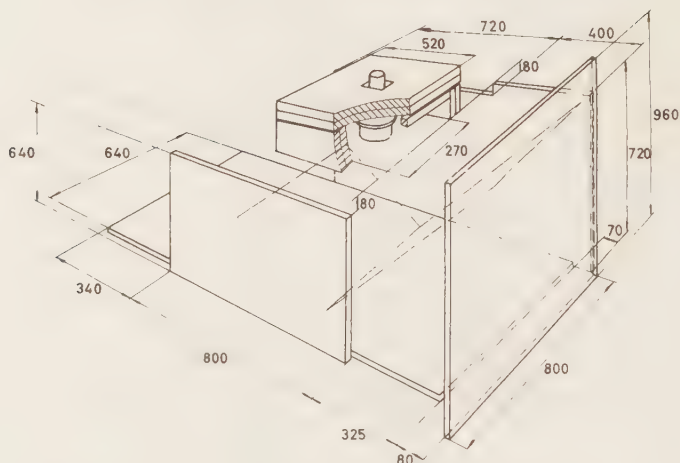


Fig. 2. Arrangement of the lead shielding of the semi-portable whole-body counter. The position of the chair is indicated by dashed-dotted lines.

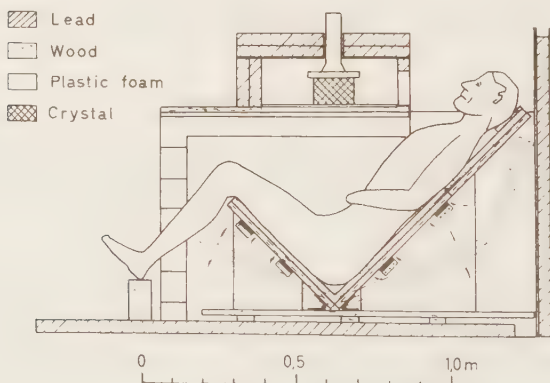


Fig. 3. Profile view showing the geometry of the semi-portable whole-body counter. The principle of the folding chair is indicated by arrows and dashed lines. The lead shield of the side walls of the counter is not shown. The crystal rests on a lucite sheet replacing the plywood area inside the lead cave.

The arrangement of the lead shielding of the semiportable whole-body counter (PC), is shown in Fig. 2. The weight of the shield is about 1 200 kg. The total weight of 1 500 kg is small enough that most floors can easily stand the counter without further support.

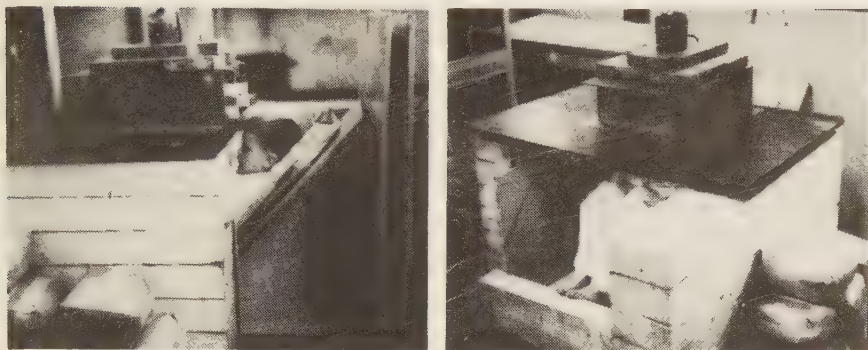


Fig. 4. The semi-portable whole-body counter seen from two different directions with a child in measuring position. The bags containing 5 kg of sugar are used for background measurements.

It was decided to avoid using a door, since this would greatly increase the complexity of construction. The outer dimensions of the counter thus constructed are only 160 cm (length) by 120 cm (width) by 110 cm (height). This small size was made possible by using a folding chair of plywood sheets (Fig. 3). The subject walks into the shield and sits down on the chair, which is folded flat on the floor. The chair is then erected to the standard chair position, until the subject sits comfortably in a well defined geometry. Since the head of the subject protrudes out of the shield (Figs 3 and 4), there is no problem of claustrophobia.

Factors influencing the background. Background studies made at our laboratory showed that additional lead would decrease the background only slowly in comparison to the amount of shielding needed. We have estimated the unshielded openings in different directions, according to Table 1, to be about 20 % of full solid angle 4π . The measured reduction of the total background counting rate was also about 80 %.

Of those openings mentioned in Table 1 (see also Fig. 2) only the first one, by closing it, could reduce the background to the expense of a reasonably small amount of lead. Measurements at our laboratory showed that a lead shield, 4 cm thick, above the stem of the photomultiplier, could reduce the background of the ^{137}Cs energy band (0.60 to 0.72 MeV) and the potassium energy band (1.38 to 1.56 MeV) with 5 and 10 %, respectively.

The improvement by adding a lead wall, 4 cm thick, at the foot end of the counter was also investigated. A wall, 64 cm wide and 48 cm high suppressed the background of the ^{137}Cs energy band by about 7 % and the background of the potassium energy band by about 6 %.

Table 1

Location of unshielded parts of the counter and their size in per cent of the full solid angle 4π (as seen from the crystal)

	%
The opening for the stem of the photomultiplier above crystal	3
The entrance of the counter	3
The upper part of the side walls	4
The foot end of the counter	6
The head end of the counter	3
All openings	19

Table 2

Background of the semi-portable whole-body counter on different locations

Location	cpm in the energy bands		Background ratio (II/I)
	I 600 to 720 keV	II 1 380 to 1 560 keV	
No 1	280	230	0.82
» 2	650	530	0.82
» 3	410	330	0.80
» 4	180	120	0.67
» 5	29	13	0.45

Place No 1: Lund (55.7° N, 14.6° E) Sweden. The counter in the middle of an air conditioned room; room dimensions: about $10 \times 5 \times 2$ m³; floor about 2 m below ground level; concrete walls, ceiling and floor.

Place No 2: Jokkmokk (66.6° N, 19.9° E) Sweden. The counter in the middle of a room of the following approximate dimensions: $4 \times 3 \times 2$ m³; floor about 2 m below ground level; concrete walls, ceiling and floor.

Place No 3: Jokkmokk (66.6° N, 19.9° E) Sweden. The counter in the middle of a room close to that of place No 2; room dimensions: about $6 \times 6 \times 2$ m³; floor about 2 m below ground level; concrete walls, ceiling and floor.

Place No 4: Inari (68.9° N, 27.0° E) Finland. The counter in the middle of a room in a wooden house; room dimensions: about $5 \times 5 \times 3$ m³; floor about one meter above ground level.

Place No 5: Lund (55.7° N, 14.6° E) Sweden. The detector in an air conditioned iron room: 210 cm by 250 cm by 195 cm (height); walls and floor, 18 cm thick, of laminated iron; the ceiling shield consists of 1 cm iron and 8 to 12 cm lead; the floor about 2 m below ground level.

In such a counter, with only moderate shielding, the background is very dependent on the environmental radiation. It was expected that our measurements in the laboratory room with concrete walls, ceiling and floor, the floor being about 2 m below ground level, would in some respects constitute an un-

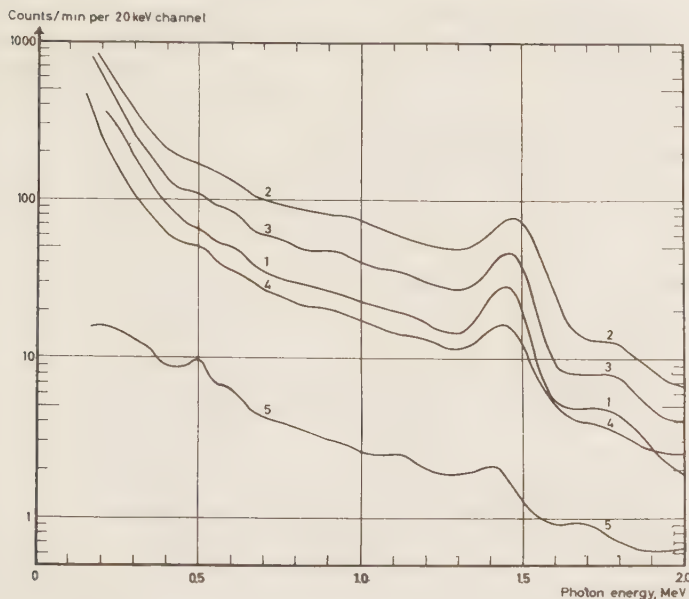


Fig. 5. Background spectra in the energy range from 0.2 to 2.0 MeV obtained in the semi-portable whole-body counter at the four places mentioned in Table 2, compared with the background in a conventional iron room (spectrum No 5). The dominant peak is mostly from potassium in the environment of the counter. Small amounts of radon daughters can be distinguished from various bumps.

favourable background situation. The background should be significantly lower in a wooden house and in a room above ground level.

The backgrounds in Table 2 are measured with a 70 kg non-radioactive sugar phantom in the counting position; it can be seen that the background of the PC could vary within wide limits, probably almost exclusively depending on the degree of radioactive contamination in the neighbourhood of the counter. The relation between the counting rate of the ^{137}Cs energy band and that of the potassium energy band shows that there is a qualitative difference between the various background spectra. The concrete is undoubtedly contaminated with radionuclides emitting high energy gamma-rays.

Background spectra, as they are obtained at places mentioned in Table 2, are shown in Fig. 5. For comparison a background from the IRC is shown too (curve No 5). Backgrounds at places Nos 2 and 3 are definitely elevated, probably due to a higher contamination level of natural radioactivity in the surroundings. The peaks and bumps can be interpreted as gamma-rays from dis-

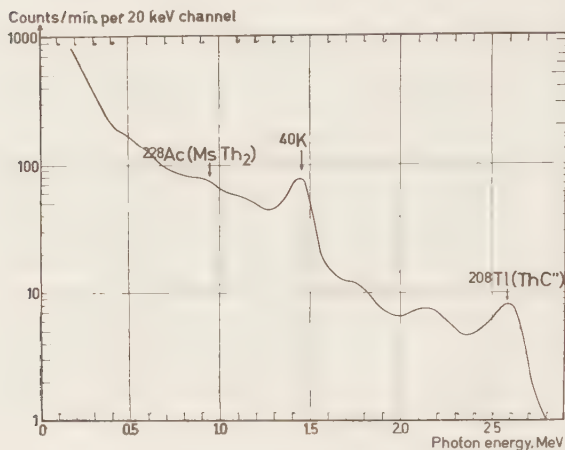


Fig. 6. Background spectrum obtained in the semi-portable whole-body counter at place No 2. The marked peak at 2.62 MeV and the bump at 0.96 MeV from thorium daughter products to some extent explain the relatively high background at this place.

integrating nuclides of the uranium and thorium series and of ^{40}K . In Fig. 6 is shown the background from place No 2 in the energy range from 0.2 MeV to 2.9 MeV. Besides the peaks and bumps noticed in Fig. 5, a peak at 2.62 MeV from ^{208}Tl of the thorium series is visible. The most predominant peak at 1.46 MeV originates from naturally occurring ^{40}K in the neighbourhood of the detector.

To be able to make accurate whole-body radioactivity determinations it is also important to take into account the effect on the background of varying body sizes. Owing to the moderate shielding, a sizable amount of background photons will be attenuated in a body placed in the counting position. Some of these will hit the crystal as degraded photons.

Photons which, in the case of empty chair, would not have hit the crystal will be directed towards the crystal by scattering processes in the body. Without passing at least 4 cm of lead, however, only those photons entering through the open foot end of the counter can hit the crystal at a scattering angle of less than 90° . Attenuation by the body of background γ -rays of a certain energy therefore will show up as a depression of the counting rate within its full energy peak. A smaller depression occurs in the energy range of its Compton distribution. Superimposed on this depressed background are then the counts from additional degraded photons scattering into the crystal by the object itself, most of them having an energy less than 511 keV.

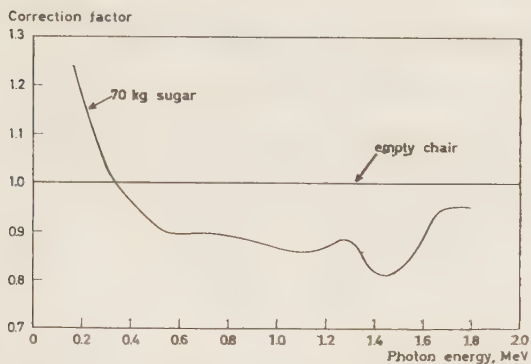


Fig. 7. The effect on the background of photon interactions in a large mass in the counting position. The background spectrum of a 70 kg sugar phantom is normalized to a background of empty chair.

The effect on the background of varying body sizes has been studied with non-radioactive sugar phantoms of several sizes in the counting position of the PC. The phantoms were made in sections of 5 kg sugar bags. They were built to resemble the shape of the body of a human being. The ratio of the background of a 70 kg phantom to that of an empty chair, as a function of the energy, is shown in Fig. 7. The correlated spectra show the effect of photon interactions in large masses inside the counter. Degraded photons will result in an elevated background counting rate of the channels below 300 keV. Above 400 keV we obtained a markedly decreased background counting rate with a 70 kg sugar phantom in comparison to that obtained without sugar in the counter. This is due to the attenuation in the phantom of photons penetrating the shield.

The background in different energy ranges shows approximately a linear relation to the phantom mass in the region from 30 to 80 kg (Fig. 8). The break of the lines of the high energy bands at about 30 kg could be a result of the attenuation of gamma-rays from the floor outside the counter. The first 30 kg sugar will obviously more effectively shield the detector from photons passing the lead floor than sugar does thereafter added to get larger phantoms. Below 300 keV, owing to scatter, there is an increasing background counting rate with the phantom size. The counting rate in the total energy range from 0.1 to 1.8 MeV also increases with the phantom size. However, for all energy bands above 400 keV the counting rate decreases with phantom size.

If a standard background is automatically or otherwise subtracted a further correction in order to get a correct net count is easily applied according to the following considerations.

$N_{b, St}$	= standard background with a phantom weight of St kg	cpm
$N_{b, X}$	= background for a person with a weight of X kg	cpm
$f_{X, St}$	= $\frac{N_{b, X}}{N_{b, St}}$ = background correction factor	
N_g	= gross count	cpm
N'_n	= $N_g - N_{b, St}$ = net count before correction	cpm
N_n	= $N_g - N_{b, X}$ = true net count for a person weighing X kg	cpm
S	= sensitivity of the whole-body counter	cpm/nc

From these definitions the following formula is deduced:

$$N_n = N'_n + N_{b, St} (1 - f_{X, St}) \quad \text{cpm (1)}$$

The correction corresponds to a body burden of

$$A_{\text{corr}} = \frac{N_{b, St}}{S} \cdot (1 - f_{X, St}) \quad \text{nc (2)}$$

At place No 1 the change of the background in the ^{137}Cs energy band, due to different body sizes in the counter, was found to be 0.11 % per kg. If a standard background with a 70 kg phantom is used and if the background is less than 700 cpm (see Table 2) this correction corresponds to less than 10 nc ^{137}Cs for a subject of 30 kg body weight.

Calibration of the semi-portable whole-body counter for absolute measurements of ^{137}Cs body burdens. The whole-body counter was constructed to have the same geometry as the '42 cm chair' arrangement of the stationary whole-body counter at Lund (CEDERQUIST & LIDÉN 1962). Therefore, the calibration data of the latter in the first approximation should be applicable to the PC.

However, a small correction of the figure of sensitivity had to be made, since the detector in the PC was supported by a lucite sheet, 4 mm thick, and the head end of the plywood roof of the counter had a 30 mm by 30 mm by 5 mm right angle iron beam. By a somewhat simplified geometrical consideration it was calculated that the absorption of the ^{137}Cs and ^{40}K gamma-rays amounted to 5.0 % and 3.4 %, respectively. Therefore the counting efficiencies of those isotopes a priori were assumed to be correspondingly smaller in the PC than in the stationary facility. Using the most recent level schemes of ^{137}Cs and ^{40}K (*Nuclear Data Sheets* 1959 and 1961) the sensitivity of the counter for these radionuclides at equilibrium in a subject of 70 kg body weight is 2.76 counts per minute per nanocurie ^{137}Cs and 0.180 counts per minute per gram potassium. The uncertainty of these figures is about 5 %.

In order to test the counting efficiency of the PC great efforts have been made to compare it with result in the IRC. Persons measured in places Nos 3 and 4 were transported by air and train to Lund to get comparable measurements as soon as possible. However, it was not possible to arrange it without a delay

Table 3

Comparable counting rates in the energy range from 0.60 to 0.72 MeV from ^{137}Cs as obtained with the same detector in the semi-portable whole-body counter and in the iron room whole-body counter at Lund

Subject	Weight of the subject kg	Counting rate		Discre- pancy (A—B) cpm	Significance of (A—B) 2 S. D. cpm
		A in PC cpm	B in IRC cpm		
Y. N.	72	185	177	8	8
J. C.	77	240	240	0	11
Y. N.	72	132	132	0	4
E. M.	61	900	903	—3	34
T. M.	34	210	199	11	13

of a couple of days. Table 3 shows the result of such measurements of different subjects in the PC and the IRC. The counting rates of the PC have been corrected for 5 % absorption in the detector supporter. All backgrounds used were obtained with non-radioactive sugar phantoms of correct weight except for subject T. M. in the PC. His background, obtained with a 65 kg sugar phantom, was corrected according to the formula (2) on page 191, using a relative background correction factor of 0.0011. All counting rates are also corrected for contribution of potassium counts in the ^{137}Cs energy band. A correction is also made on the assumption of a daily excretion rate of 1 %. Table 3 does not indicate any difference in the counting efficiency between the compared whole-body counters.

In the PC, children down to about 25 kg body weight were assumed to be measured. Therefore it was desirable to take into account the relation between the counting efficiency and the body weight. The iron room counter was calibrated for ^{137}Cs in the body for a standard man. The efficiency variation with the body weight was not very particularly studied. With a 7" in diam. by 3.5" thick NaI crystal, MILLER et coll. (1959) have shown that the variation is less than 5 % of the sensitivity of potassium for a change in body weight from 50 to 96 kg. With a 8" diam. $\times$ 4" thick NaI crystal, MILLER 1962 reported results indicating a variation of the sensitivity for potassium in the body of about 10 % for a change of 50 kg in body weight. In our laboratory, using a 5" $\times$ 4" NaI (TI) crystal, a decrease in the efficiency of about 10 %, for a change in body weight from 50 to 100 kg, has been found.

Measurements of cylindrical plastic containers filled with solutions of $^{137}\text{CsCl}$ have shown a rather wide variation of the counting efficiency for different parts of the body, as could be expected from simple geometrical considerations (Fig. 9). Each of the four sections consisting of two cylindrical plastic containers were counted, while the other three were replaced by non-radioactive sugar

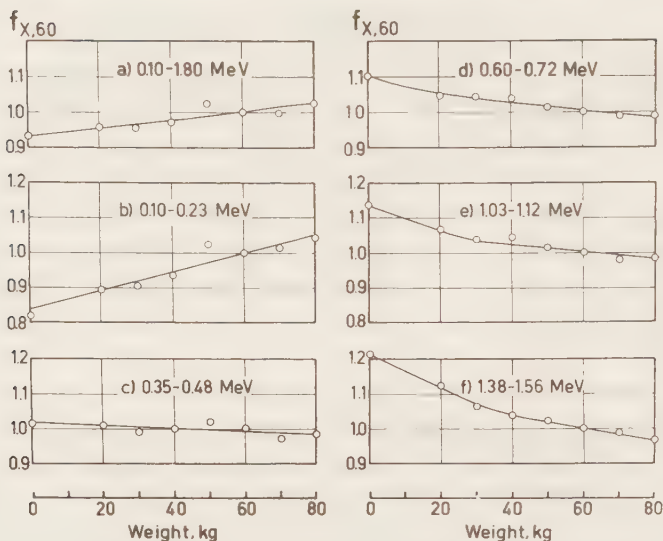


Fig. 8. The background correction factor ($f_{X,60}$) for different energy intervals obtained with several sizes of the sugar phantom. Above 400 keV, due to attenuation, the background decreases with increasing mass. In the low energy part of the spectrum, due to additional degraded photons, the background increases with the phantom mass.

bags. The figures indicate the relative counting efficiency. They show that radioactivity in the lower parts of the legs is counted with a rather low efficiency. By weighing the contribution to the counting efficiency of different parts of the phantom it was possible to get an idea of the variations with body weight below 50 kg. The weight of the different counting efficiencies was obtained from a consideration of both the body size and the distribution of muscles within subjects with body weights of 25 and 50 kg, respectively. This calculation indicates a variation of the efficiency of 0.3 to 0.5 % per kg body weight from 25 to 50 kg, the efficiency being higher for small body sizes.

A direct measurement in the PC of a phantom of plastic cylinders containing ^{137}Cs solution and resembling a subject of 20 to 25 kg body weight gave a sensitivity which was 19 % higher than that obtained with subjects of standard weight. This corresponds to an average change of sensitivity of about 0.4 % per kg from 25 to 75 kg.

From these considerations a variation of 0.3 to 0.5 % per kg from 20 to 50 kg and 0.2 to 0.3 % per kg from 50 to 100 kg body weight should be a rather good approximation.

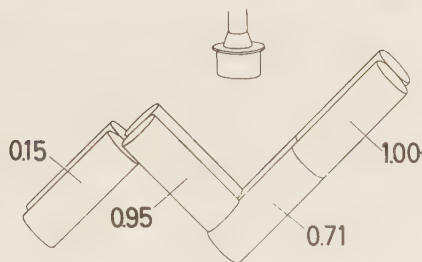


Fig. 9. A simple synthesized phantom consisting of 4 compartments of double cylindrical containers. The figures indicate the relative counting efficiency of the different compartments.

Since this counter is constructed for measurements of relatively high body burdens of ^{137}Cs , the contribution of potassium counts in the ^{137}Cs energy band is of little importance. These counts should never correspond to more than 4 nc ^{137}Cs . However, in most normal cases they correspond to about 1 nc ^{137}Cs for subjects below 50 kg body weight, for heavier persons about 2 nc ^{137}Cs .

The considerations above lead to the following general formula for determination of the body content (A_{Cs}) of ^{137}Cs in human beings.

$$A_{\text{Cs}} = \left[\frac{\text{cpm}_{\text{Cs}}}{2.76 [1 + 0.004 (70 - w)]} - \begin{cases} 2; & w > 50 \text{ kg} \\ 1; & w \leq 50 \text{ kg} \end{cases} \right] \text{nc } ^{137}\text{Cs} \quad (3)$$

where cpm_{Cs} is the net counting rate in the interval of 0.60 to 0.72 MeV and w is the body weight of the subject.

Counting accuracy

The most important factor determining the accuracy in the evaluation of body burdens of radioactive isotopes is governed by the random occurrence of the pulses. Table 4 shows the statistical accuracy of the determination of body burdens of ^{137}Cs as indicated by one S.D. in per cent of the number of net counts. The calculation is made on the assumption of counting times from 10 to 60 minutes, for body burdens from 5 to 500 nc ^{137}Cs , and for three different background counting rates. The first one corresponds to the relatively high background level at the place No 2 of Table 2. The second background represents a rather good counting situation for the PC at place No 4 of Table 2. For comparison, the statistical accuracy of the IRC at Lund is calculated where the background counting rate is about 30 cpm in the same energy band. In all cases the sensitivity is assumed to be 2.76 cpm/nc. From Table 4 it is calculated that the greatest standard deviation for a 10 minute gross count and a 10 minute background count corresponds to about 4 nc ^{137}Cs , independent of the body burden of this isotope. If 2 S.D. is used as a measure of the statistical accuracy, the uncertainty owing to statistical fluctuations is less than 9 nc ^{137}Cs .

Table 4

The statistical accuracy expressed as one S. D. in per cent of the number of net counts (the calculation is made for a sensitivity of 2.76 counts per minute per nanocurie of ^{137}Cs and for the same counting time of subject and background)

Counting time, min	Background cpm	Body burdens, nc ^{137}Cs						
		5	10	20	50	100	200	500
10	650	83	42	21	8	5	2	1
	180	44	22	12	5	3	2	1
	30	20	11	6	3	2	1	<1
20	650	59	30	15	6	3	2	<1
	180	31	16	8	4	2	1	<1
	30	14	8	4	2	1	1	<1
60	650	34	17	9	3	2	1	<1
	180	18	9	5	2	1	<1	<1
	30	8	4	3	1	<1	<1	0.4

The accuracy in the determination of body contents of ^{137}Cs is highly governed by the stability of the background, which in most cases is a matter of holding the radon ^{daughter} concentration at a constant level in the surroundings of the counter. With fluctuating weather conditions the radon concentration is subject to considerable variation. Since the radon daughter products, especially RaC, have several γ -ray lines above 0.6 MeV, this varying radon concentration will effect the background counting rate in the ^{137}Cs energy band. At the places Nos 2 and 4, the maximum deviation from the average of frequently measured 10 minute backgrounds of the ^{137}Cs energy band was about 2 S.D. This variation was too small to be significantly attributed to a varying radon concentration. Therefore with very simple precautions the uncertainty owing to this variation probably should correspond to less than 2 nc ^{137}Cs .

The superficial radon contamination of the subject itself is a problem of the same nature. The only real cure is a shower for the subject, especially his hair, and a change of clothes before measurements. Without any precautions the superficial radon contamination could result in false counts in the ^{137}Cs energy band, corresponding to several nc ^{137}Cs in excess of the real body content.

The background depression owing to the subject in the counter also could give an error if the background phantom in its scattering properties does not sufficiently well resemble the subject. The magnitude depends on the background level. In our case this error should not correspond to more than 2 nc ^{137}Cs .

The correction for potassium counts distributed in the ^{137}Cs energy band is certainly assessed within 1 nc ^{137}Cs .

Summed up, a carefully evaluated value of a subject's body burden of ^{137}Cs from a 10 minute measurement in the PC should not be in error by more than 15 nc ^{137}Cs .

It is the opinion of the authors that this simple counter could find applications for medical and other survey purposes, in many cases offering a good alternative to the more complex and expensive whole-body counters of the 'iron room' type.

Acknowledgements

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Addendum in the proofs

Recently (in March and April, 1963) the counter was used as a mobile unit in a big motor bus. The counter was placed in the middle of the bus. The floor of the counter was about 80 cm above ground level. The mobile unit was used at a distance of less than 20 m from the rooms defined as place No 2 and place No 3 in Table 2. The backgrounds of the energy bands I and II were then 150 cpm and 85 cpm, respectively. The background ratio (II/I) was 0.57. At 8 different places along more than a 2 000 km long road from northern to southern Sweden the background of band I varied from 110 cpm to 230 cpm. The background of band II varied from 65 cpm to 130 cpm and the background ratio from 0.48 to 0.73.

SUMMARY

A whole-body counter for determination of body burdens of ^{137}Cs and other isotopes is described. The counter, easily assembled and disassembled, has small dimensions and the weight is less than 1 500 kg. The background reduction is obtained by lead shielding. The effect on the background of the radioactive environment and of the size of the subject has been studied. The measuring geometry, a $5'' \times 4''$ NaI(Tl) crystal in a 42 cm chair geometry, has been calibrated by comparison with a static iron-room counter. The sensitivity is 2.76 cpm nc ^{137}Cs . The measuring accuracy as a function of body burden and background is analysed.

ZUSAMMENFASSUNG

Ein Ganzkörperzähler für Bestimmung der Mengen von ^{137}Cs und anderen radioaktiven Isotopen im menschlichen Körper wird beschrieben. Der Zähler, der leicht auf- und abgebaut werden kann, ist verhältnismässig klein und wiegt weniger als 1 500 kg. Die Abhängigkeit des Nulleffekts von der radioaktiven Kontamination der Umgebung und von der Körpergrösse sind studiert worden. Der Ganzkörperzähler, ein Natriumjodidkristall (12,5 cm $\times$ 10 cm) in „42 cm Stuhlgeometrie“ ist mit Hilfe von Vergleichsmessungen mit einem statio-

nären Stahlkammerzähler kalibriert worden. Die Empfindlichkeit wurde als 2,76 Imp/min pro nc 137 Cs festgestellt. Die Abhängigkeit der Messgenauigkeit von der Körperaktivität und von der Grösse des Nulleffekts wird analysiert.

RÉSUMÉ

Les auteurs décrivent un compteur humain total pour la mesure de la charge du corps humain en 137 Cs et en autres isotopes. Ce compteur, facilement monté et démonté, est de petites dimensions et pèse moins de 1 500 kg. La réduction du bruit de fond est obtenue par un blindage de plomb. L'effet de la radioactivité ambiante et des dimensions du sujet sur le bruit de fond a été étudié. La géométrie du dispositif de mesure, un cristal de NaI (Tl) de 5×4 pouces distant de 42 cm du fauteuil, a été étalonnée par comparaison avec un compteur fixe dans une chambre blindée de fer. Sa sensibilité est de 2,76 cpm/nc 137 Cs. L'exactitude de la mesure en fonction de la charge du corps humain et du bruit de fond a été étudiée.

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THE ENHANCED RADIOCAESIUM LEVELS OF PEOPLE IN NORTHERN SWEDEN

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Abstract — Résumé — Аннотация — Resumen

THE ENHANCED RADIOCAESIUM LEVELS OF PEOPLE IN NORTHERN SWEDEN. After the discovery of the high caesium-137 body activity of Swedish Lapps early in 1961 measurements were performed on large groups of Lapps and other Swedes on a similar diet. In September, 1961 162 persons from an area close to the arctic circle were measured in a semi-portable whole-body counter. In the Lapp group caesium-137 levels ranging from 15 to 690 nc were found. At the same place a group of 157 persons were counted in April, 1962. At that time the caesium-137 range was 30 to 740 nc. During a five weeks' expedition to seven different centres in northern Sweden in April, 1963 a total number of 458 persons were studied by means of the same counter set up in a bus. The caesium-137 range for Lapps in the above mentioned area was then 50 to 900 nc. The average caesium-137 body activity of all the adult male reindeer breeders (78 persons) measured in April, 1963 was 461 nc. The maximum body activity found was 1340 nc caesium-137. Details are presented on the variation of caesium-137 in human beings with age, sex, occupation and diet as well as on the seasonal and geographical variations found. An increase in the average caesium-137 body activity has been observed from 1961 to 1963. For comparison, non-Lapps have also been counted. Almost all of them also show a substantially enhanced caesium-137 level if compared with persons in southern Sweden.

The radiation dose from caesium-137 is in many cases two to three times as large as the potassium-40 dose, the observed maximum giving a dose eight times that of the potassium dose.

CHARGE CORPORELLE DE RADIOCÉSIIUM RELATIVEMENT ÉLEVÉE CHEZ LES HABITANTS DE LA SUÈDE SEPTENTRIONALE. Lorsqu'on eut découvert au début de 1961 que la charge corporelle de césium 137 était élevée chez les Lapons de Suède, on a fait des dosages sur des groupes importants de Lapons et d'autres habitants de la Suède qui suivent un régime alimentaire analogue. En septembre 1961, on a effectué des dosages sur 162 personnes d'une région située à proximité du cercle arctique au moyen d'un anthropogammamètre semi-portatif. Chez les Lapons, on a relevé des charges corporelles de césium 137 allant de 15 à 690 nc. En avril 1962, on a fait des dosages sur un autre groupe de 157 personnes de la même région. Les charges de césium 137 allaient alors de 30 à 740 nc. En avril 1963, une expédition qui, en cinq semaines, s'est rendue dans sept centres de la Suède septentrionale a fait des dosages sur un total de 458 personnes au moyen du même appareil monté sur un autobus. Cette fois-là, les charges de césium 137 chez les Lapons de cette région allaient de 50 à 900 nc. La charge corporelle moyenne de césium 137 pour tous les éleveurs de rennes - soit un groupe de 78 personnes - mesurée en avril 1963 s'élevait à 461 nc. La charge corporelle maximum était de 1340 nc. Le mémoire présente des détails sur les variations des charges de radiocésium chez l'homme selon l'âge, le sexe, l'occupation et le régime alimentaire, ainsi que sur les fluctuations saisonnières et géographiques qui ont été relevées. On a observé un accroissement de la charge corporelle moyenne de césium 137 de 1961 à 1963. Aux fins de comparaison, on a également fait des dosages sur des habitants des mêmes régions autres que lapons. Chez presque tous, la charge de césium 137 était sensiblement supérieure à celle qui a été trouvée chez les habitants de la Suède méridionale.

La dose de rayonnement due au radiocésium est, dans bien des cas, de deux à trois fois la dose qui provient du potassium 40, le maximum observé étant de huit fois cette dose.

ПОВЫШЕННОЕ СОДЕРЖАНИЕ РАДИОАКТИВНОГО ЦЕЗИЯ В ОРГАНИЗМЕ У ЖИТЕЛЕЙ СЕВЕРНОЙ ШВЕЦИИ. После обнаружения высокого содержания цезия-137 в организме у шведских лопарей в начале 1961 года было проведено обследование больших групп лопарей и других жителей Швеции, получающих такую же диету. В сентябре 1961 года обследовали 162 человека из района, примыкающего в Арктическому кругу; измерения производились с помощью полупереносного счетчика для измерения радиоактивности всего организма. В группе лопарей содержание цезия-137 находилось в пределах от 15 до 690 мккюри. В этом же районе в апреле 1962 года была обследована группа из 157 человек. В это время

уровень цезия-137 составлял 30–740 ммкюри. Во время 5-недельной экспедиции в 7 различных центрах северной Швеции в апреле 1963 года было обследовано 458 человек с помощью той же счетной установки, размещенной в автобусе. Уровень цезия-137 у лопарей в указанном районе в это время составлял 50–900 ммкюри. Среднее содержание цезия-137 у взрослых мужчин-оленьеводов в апреле 1963 года составляло 461 ммкюри (группа из 78 человек). Максимальное содержание цезия-137 составляло 1340 ммкюри. Представлены подробные данные относительно колебаний содержания радиоактивного цезия у людей в зависимости от возраста, пола, профессии и диеты, а также от сезонных и географических показателей. Наблюдалось повышение среднего содержания цезия-137 в организме в течение 1961–1963 годов. Для сравнения были проведены измерения у шведов, живущих в тех же округах, что и лопари. Почти у всех было обнаружено значительное повышение содержания цезия-137 в организме по сравнению с жителями Южной Швеции.

Внутренняя доза, создаваемая радиоактивным цезием, обычно в 2–3 раза больше дозы Калия-40 при максимуме, в 8 раз превышающем дозу калия.

CARGAS DE RADIOCESIO ANORMALMENTE ELEVADAS EN LOS HABITANTES DEL NORTE DE SUECIA. Después de descubrirse a principios de 1961 la elevada carga corporal de cesio-137 que tenían los lapones suecos, se han efectuado mediciones en grandes grupos de lapones y otros habitantes de Suecia que siguen un régimen alimenticio análogo. En septiembre de 1961 se examinaron 162 personas de una zona próxima al Círculo polar ártico con un antropogammámetro semiportátil. En los lapones se registraron cargas de cesio-137 comprendidas entre 15 y 690 nc. En la misma región, se sometió a recuento en abril de 1962 a un grupo de 157 personas. En esta ocasión la carga de cesio-137 osciló entre 30 y 740 nc. En el curso de una expedición que en cinco semanas visitó a siete centros de Suecia septentrional en abril de 1963, se examinaron en total 458 personas con el mismo contador montado en un ómnibus. Esta vez, la carga de cesio-137 de los lapones de la zona antes mencionada estuvo comprendida entre 50 y 900 nc. La carga media de cesio-137 en todos los criadores de renos (78 hombres adultos), medida en abril de 1963, fue de 461 nc. La carga corporal máxima observada fue de 1340 nc de cesio-137. Se facilitan detalles sobre la variación de la carga de cesio-137 en función de la edad, el sexo, el tipo de ocupación y el régimen alimenticio, así como sobre las variaciones estacionales y geográficas observadas. De 1961 a 1963 se ha advertido un aumento de la carga corporal media de cesio-137. Con fines comparativos, se sometió también a recuento a individuos no lapones. En casi todos ellos se observó una carga de cesio-137 muy elevada en comparación con la de los habitantes del sur de Suecia.

La dosis de irradiación debida al cesio-137 suele ser dos o tres veces mayor que la debida al potasio-40, siendo el máximo observado 8 veces mayor.

1. INTRODUCTION

Early in 1961 unexpectedly high Cs^{137} levels were found in some people from northern Sweden. Whole-body measurements in Lund revealed body activities in the 300 nc range [1].

At the same time reindeer meat was shown to have a high specific Cs^{137} activity (from 5 to 50 nc/kg fresh weight) [1, 2]. Since reindeer meat constitutes an important part of the diet in northern Sweden, especially of the Lapps, large groups of people could be expected to have enhanced Cs^{137} body activities. Our body activity measurements in September, 1961 at Jokkmokk (67°N, 20°E), Sweden verified this assumption. The same Cs^{137} level was found in people in October, 1961 from a study by MIETTINEN *et al.* [3] (in collaboration with the present authors) at Inari (69°N, 27°E), Finland. Furthermore, two male Lapps from Kautokeino (69°N, 23°E), Norway were counted at our laboratory at the end of October, 1961 and they showed activities of 205 and 390 nc [4].

High body activities have also been found in Alaska, United States by PALMER *et al.* [5].

2. INVESTIGATION No. 1

In September, 1961 a body-activity investigation was carried out at Jokkmokk in northern Sweden. One hundred and sixty-two subjects were counted by means of transportable whole-body counting equipment [6], and a rough estimate of the diet of meat, fish and milk was obtained from an interview of all subjects.

This investigation was planned before the nuclear weapon tests started in 1961 and was performed before the new global fall-out reached Sweden. The results from these measurements therefore will serve as a reference base for the measurements performed later.

The subjects studied were invited to participate in the investigation by means of announcements on the radio and in the newspapers. The composition of the population sample and the body activities obtained can be seen in Table I. Efforts were made to get about the same number of Lapps and non-Lapps, males and females, and adults and children. With some effort we also succeeded in getting four vegetarians.

3. INVESTIGATION No. 2

Atmospheric nuclear weapon tests in the autumn of 1961 made it important to follow up the activity levels. A new study was undertaken at the same place in April, 1962. In this case 157 subjects were investigated. About the same sampling method was used as in the first investigation, but special efforts were made to secure a better representation in certain groups. However, it was difficult to get the same subjects again. The results of the second investigation (Table II) are therefore not fully comparable with the results of the first investigation. The results of the measurements of those subjects also measured in September, 1961 are shown in Table III. A diet investigation was also performed by an interview method. Some results of investigations Nos 1 and 2 were reported earlier [7].

4. INVESTIGATION No. 3

In April, 1963 a new more extensive investigation was performed. The whole-body counting equipment was mounted in a bus. Measurements were performed at Jokkmokk, but also at six other places in northern Sweden. These places were chosen since they are centres of Lapp communities with not too small a population. The places visited are shown on the map in Fig. 1; they are also listed in Table IV.

The subjects to be investigated were randomly selected from demographic tables, and they were invited in advance. From earlier investigations we learned that urban people had quite low body activities, in general below 30 nc. Therefore it was decided to compare the Lapps with non-Lapps, farmers and lumbermen. This group was sufficiently homogeneous and also to some extent had living conditions in common with Lapps.

Three hundred and ninety-eight Lapps were selected from a list made in 1958 [8]. Some of these people had died or moved away from the place.

TABLE I

Cs¹³⁷ LEVELS IN HUMAN BEINGS, OBTAINED BY WHOLE-BODY COUNTING AT JOKKMOKK (66.6°N, 19.9°E), SWEDEN IN SEPTEMBER, 1961

Group	Sex	Age (yr)	Number of subjects	Body activity of Cs ¹³⁷							
				Average		Median		Maximum		Minimum	
				nc	nc/kg	nc	nc/kg	nc	nc/kg	nc	nc/kg
<u>Lapps</u> Reindeer-breeders Non-reindeer breeders Children	M	20-65	28	336	5.14	301	4.39	689	9.47	152	2.54
	F	20-65	5	207	3.72	161	3.60	368	6.03	151	2.52
	M	20-65	6	172	2.63	166	2.46	333	4.57	48	0.86
	F	20-65	4	136	2.68	146	2.73	207	4.14	45	1.12
	M	10-13	8	99	3.20	90	2.72	139	4.87	78	2.38
	M	14-19	-	-	-	-	-	-	-	-	-
	F	10-13	16	93	2.52	84	2.05	154	3.81	60	1.50
	F	14-19	14	92	1.96	82	1.77	239	3.99	<15	0.29
<u>Non-Lapps</u>	M	20-65	13	76	1.08	84	1.20	137	2.05	<15	<0.25
	F	20-65	15	47	0.76	33	0.66	130	2.15	<15	<0.25
	M	10-19	29	27	0.50	19	0.35	122	1.94	<15	<0.25
	F	10-19	20	21	0.41	15	0.30	39	0.91	<15	<0.25
Vegetarians	Mixed		4	20	0.34	19	0.33	28	0.56	<15	<0.25

TABLE II

Cs¹³⁷ LEVELS IN HUMAN BEINGS, OBTAINED BY WHOLE-BODY COUNTING AT JOKKMOKK, SWEDEN IN APRIL, 1962

Group	Sex	Age (yr)	Number of subjects	Body activity of Cs ¹³⁷							
				Average		Median		Maximum		Minimum	
				nc	nc/kg	nc	nc/kg	nc	nc/kg	nc	nc/kg
<u>Lapps</u> Reindeer- breeders	M	20 - 65	35	435	7.08	413	7.33	740	11.75	222	2.78
	F	20 - 65	15	230	4.12	218	4.17	355	6.00	144	2.43
	M	20 - 65	6	227	3.64	177	2.96	478	6.55	74	1.35
	F	20 - 65	12	139	2.87	132	2.79	231	5.26	47	1.23
	M	10 - 13	10	78	2.46	69	2.04	134	4.34	31	1.39
	M	14 - 19	4	193	3.68	168	3.01	325	5.08	110	2.76
Non-reindeer- breeders	F	10 - 13	11	109	3.02	98	2.67	172	4.84	51	1.64
	F	14 - 19	15	122	2.63	122	2.75	266	4.66	34	0.79
<u>Non-Lapps</u>	M	20 - 65	16	148	2.17	151	2.40	363	4.72	18	0.27
	F	20 - 65	15	107	1.91	80	1.62	277	4.83	22	0.41
Children	M	10 - 19	7	78	1.43	80	1.55	140	2.45	20	0.67
	F	10 - 19	11	61	1.43	56	1.39	91	2.34	42	0.71

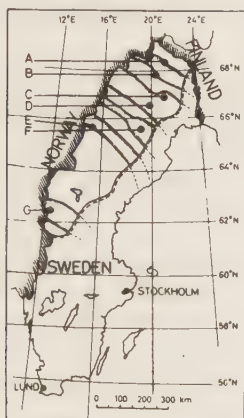


Fig. 1

Map of Sweden showing the area of special interest in this investigation

----- Approximate limit of area normally used for reindeer breeding

////// Approximate limit of area reserved for the reindeer herds of the Lapp communities being studied

The places listed in Table IV are indicated by capitals

If this number of subjects is omitted from the original list, 60 to 65% came to the investigation. Of 195 non-Lapps invited 68% came. Besides these

TABLE IV

PLACES VISITED BY THE MOBILE LABORATORY
DURING THE INVESTIGATION OF BODY ACTIVITIES
IN APRIL, 1963 (cf map in Fig. 1)

Place	Code	Latitude (°N)	Longitude (°E)	Altitude above sea level (m)
Övre Soppero	A	68.9	21.4	360
Jukkas järvi	B	67.8	20.5	330
Pumu	C	66.9	21.2	530
Jokkmokk	D	66.6	19.8	260
Tärnaby	E	65.7	15.3	440
Arvidsjaur	F	65.6	19.1	370
Funäsdalen	G	62.5	12.5	580

selected subjects, for various reasons about 100 additional persons were investigated.

Parallel to the whole-body counting a dietary investigation was performed by an interview method. Samples of reindeer meat, fish and cow's milk were also collected for a gamma spectrometric assay.

This paper primarily contains results of the whole-body counting measurements. An evaluation of the diet investigation will be made elsewhere [9].

Tables V and VI give the body activity of groups of Lapps and non-Lapps in the seven different areas. The number of subjects is indicated in brackets and both the activity and the specific activity are given.

In Table VII the subjects from the different areas are put together to show age and sex dependence for Lapps and non-Lapps.

Table VIII compares the Jokkmokk results in 1962 and 1963 for a control group of 48 Lapps and seven non-Lapps.

5. DISCUSSION OF THE RESULTS

5.1. *Annual variation due to change of diet*

The increase found from September, 1961 to April, 1962 (Tables I to III) is assumed to be mostly a result of the annual variation of the diet. Dietary investigations and radio assays of food samples have shown that the primary intake of Cs^{137} is through reindeer meat [3, 7, 9]. These studies also showed an annual variation of the intake, partly due to a variation of the amount of reindeer meat in the diet, and partly due to an annual variation of the specific activity of the reindeer meat, winter meat sometimes being about five times more active. The minimum value of the body activity of Lapps should appear in the autumn and the maximum late in the spring or beginning of the summer.

For most Lapps (a population of about 3000) reindeer meat constitutes a large part of the diet, often about 500 g/d. During the summer time reindeer meat is to some extent replaced by fresh-water fish.

For non-Lapps reindeer meat is more exclusively a winter constituent of the diet. But even during winter time the meat consumption is several times lower than for the Lapps. Many urban people seldom eat reindeer meat. In 1961 they had a body activity of less than 30 nc, i.e. about the same level as the vegetarians (Table I).

Non-Lapps engaged in hard manual labour eat somewhat more reindeer meat than urban people. Their body activity was about the same as for several Lapps.

When comparing the results from 1961 and 1962 in Tables I and II an increase was noticed for almost all the groups, for Lapps in general between 10 and 40%. For non-Lapps the spring values were 100 to 200% higher than the autumn values.

Since the groups were not composed exactly of the same subjects on both occasions, it was difficult to calculate a representative figure of the increase. However, 71 of those subjects measured in 1961 were also measured in April 1962 (Table III). An analysis of the group of 11 male reindeer breeders demonstrates the difficulty in assigning a figure for the annual variation. Three of the subjects actually decreased. The interview revealed

TABLE V

LAPP GROUPS FROM SEVEN DIFFERENT AREAS IN NORTHERN SWEDEN
The Cs137 body activity (nc) and the specific body activity (nc/kg) in April 1963*

Age	Sex	A	B	C	D	E	F	G	Average
11 - 20	M	166 (10)	82 (4)	155 (8)	194 (4)	110 (1)	355 (6)	313 (3)	200 (36)
		<u>3.99</u>	<u>2.19</u>	<u>3.43</u>	<u>5.41</u>	<u>1.80</u>	<u>6.30</u>	<u>6.69</u>	<u>4.37</u>
	F	114 (10)	56 (1)	90 (5)	136 (12)	36 (1)	136 (3)	-	117 (32)
		<u>2.94</u>	<u>1.14</u>	<u>2.14</u>	<u>3.20</u>	<u>1.03</u>	<u>2.60</u>		<u>2.76</u>
21 - 40	M	351 (3)	388 (1)	583 (5)	413 (9)	-	605 (6)	497 (10)	490 (34)
		<u>5.36</u>	<u>5.39</u>	<u>8.25</u>	<u>6.36</u>		<u>10.30</u>	<u>7.28</u>	<u>7.49</u>
	F	202 (4)	178 (3)	212 (6)	213 (8)	146 (3)	242 (5)	244 (3)	209 (32)
		<u>2.91</u>	<u>3.23</u>	<u>3.56</u>	<u>4.31</u>	<u>2.66</u>	<u>4.70</u>	<u>3.98</u>	<u>3.77</u>
41 - 65	M	399 (6)	494 (6)	351 (1)	489 (11)	290 (3)	362 (10)	536 (7)	439 (44)
		<u>6.53</u>	<u>7.47</u>	<u>6.27</u>	<u>7.73</u>	<u>4.52</u>	<u>6.28</u>	<u>8.17</u>	<u>7.02</u>
	F	297 (6)	134 (3)	-	283 (4)	236 (4)	172 (12)	286 (11)	237 (40)
		<u>4.78</u>	<u>2.40</u>		<u>4.76</u>	<u>3.46</u>	<u>3.06</u>	<u>4.74</u>	<u>3.94</u>

* The different areas are indicated by capitals according to Table IV. Figures in brackets indicate the number of randomly selected subjects.

TABLE V (cont'd)

Age	Sex	A	B	C	D	E	F	G	Average
11 - 65	M	269 (19) <u>5.05</u>	335 (11) <u>5.36</u>	322 (14) <u>5.35</u>	411 (24) <u>6.83</u>	245 (4) <u>3.84</u>	426 (22) <u>7.38</u>	483 (20) <u>7.50</u>	379 (114) <u>6.33</u>
	F	187 (20) <u>3.49</u>	142 (7) <u>2.58</u>	157 (11) <u>2.92</u>	186 (24) <u>3.83</u>	177 (8) <u>2.86</u>	184 (20) <u>3.40</u>	277 (14) <u>4.58</u>	191 (104) <u>3.53</u>
Average		277 (39) <u>4.25</u>	260 (18) <u>4.28</u>	249 (25) <u>4.28</u>	299 (48) <u>5.33</u>	200 (12) <u>3.18</u>	311 (42) <u>5.49</u>	398 (34) <u>6.30</u>	289 (218) <u>4.99</u>
Median		215 (39) <u>3.44</u>	177 (18) <u>2.89</u>	161 (25) <u>3.34</u>	254 (48) <u>4.86</u>	192 (12) <u>3.28</u>	264 (42) <u>4.79</u>	335 (34) <u>5.47</u>	257 (218) <u>4.46</u>
Median radiation dose mrad/a		28	23	27	39	26	38	44	36

TABLE VI

NON-LAPP GROUPS (FARMERS) FROM SEVEN DIFFERENT AREAS IN NORTHERN SWEDEN

The Cs¹³⁷ body activity (nc) and the specific body activity (nc/kg) in April 1963*

Age (yr)	Sex	A	B	C	D	E	F	G	Average
11-20	M	78 (5) <u>1.98</u>	37 (2) <u>0.71</u>	43 (2) <u>0.84</u>	70 (3) <u>1.44</u>	53 (1) <u>0.80</u>	93 (2) <u>1.49</u>	72 (1) <u>1.33</u>	67 (16) <u>1.40</u>
	F	86 (6) <u>1.87</u>	43 (3) <u>0.81</u>	55 (3) <u>1.14</u>	46 (4) <u>0.95</u>	13 (1) <u>0.30</u>	26 (1) <u>0.51</u>	13 (2) <u>0.25</u>	53 (20) <u>1.11</u>
21-40	M	309 (3) <u>4.44</u>	-	326 (3) <u>4.87</u>	185 (5) <u>2.73</u>	72 (1) <u>1.25</u>	108 (4) <u>1.47</u>	147 (4) <u>2.01</u>	196 (20) <u>2.84</u>
	F	159 (4) <u>2.80</u>	101 (2) <u>1.28</u>	30 (2) <u>0.57</u>	46 (6) <u>0.78</u>	49 (2) <u>0.85</u>	76 (5) <u>1.14</u>	20 (2) <u>0.31</u>	74 (23) <u>1.20</u>
41-65	M	272 (7) <u>3.61</u>	142 (3) <u>1.72</u>	146 (2) <u>1.78</u>	177 (9) <u>2.40</u>	180 (1) <u>2.25</u>	132 (2) <u>1.80</u>	94 (3) <u>1.12</u>	183 (27) <u>2.40</u>
	F	170 (6) <u>2.27</u>	111 (5) <u>1.60</u>	52 (1) <u>0.76</u>	168 (3) <u>3.04</u>	47 (2) <u>0.69</u>	89 (5) <u>1.46</u>	112 (5) <u>1.51</u>	120 (27) <u>1.77</u>

* The different areas are indicated by capitals according to Table IV. Figures in brackets indicate the number of randomly selected subjects.

TABLE VI (cont'd)

Age (yr)	Sex	A	B	C	D	E	F	G	Average
11 - 65	M	215 (15) <u>3.23</u>	100 (5) <u>1.32</u>	194 (7) <u>2.84</u>	160 (17) <u>2.33</u>	102 (3) <u>1.43</u>	110 (8) <u>1.56</u>	118 (8) <u>1.59</u>	158 (63) <u>2.29</u>
	F	136 (16) <u>2.25</u>	89 (10) <u>1.30</u>	461 (6) <u>0.89</u>	74 (13) <u>1.35</u>	41 (5) <u>0.68</u>	77 (11) <u>1.23</u>	70 (9) <u>0.97</u>	86 (70) <u>1.39</u>
Average		174 (31) <u>2.72</u>	92 (15) <u>1.31</u>	126 (13) <u>2.29</u>	123 (30) <u>1.91</u>	64 (8) <u>0.96</u>	91 (19) <u>1.37</u>	92 (17) <u>1.26</u>	120 (133) <u>1.82</u>
Median		138 (31) <u>2.46</u>	83 (15) <u>1.14</u>	52 (13) <u>0.77</u>	85 (30) <u>1.57</u>	56 (8) <u>0.80</u>	52 (19) <u>0.93</u>	73 (17) <u>0.98</u>	85 (133) <u>1.47</u>
Median radiation dose mrad/a		20	9	6	13	6	7	8	12

TABLE VII

THE AVERAGE SPECIFIC BODY ACTIVITY OF Cs¹³⁷ (nc/kg) IN DIFFERENT AGE GROUPS OF LAPPS AND CONTROLS OF NON-LAPPS (FARMERS) IN NORTHERN SWEDEN IN APRIL, 1963*

Age (yr)	Lapps			Non-Lapps		
	Males (A) nc/kg	Females (B) nc/kg	Sex ratio B/A	Males (C) nc/kg	Females (D) nc/kg	Sex ratio D/C
11 - 13	3.20 (15)	2.47 (11)	0.77	1.52 (5)	1.21 (6)	0.80
14 - 16	3.98 (11)	2.91 (13)	0.73	1.31 (9)	0.99 (9)	0.76
17 - 20	6.56 (10)	2.91 (8)	0.44	2.21 (10)	1.04 (8)	0.47
21 - 30	6.54 (14)	3.22 (15)	0.49			
31 - 40	8.07 (20)	4.25 (17)	0.53	3.14 (12)	1.26 (20)	0.40
41 - 50	7.83 (20)	4.27 (18)	0.55	2.44 (12)	1.69 (12)	0.69
51 - 65	6.46 (24)	3.66 (22)	0.57	2.35 (15)	1.83 (15)	0.78

* Figures in brackets indicate the number of randomly selected subjects.

that they had been herding during the summer of 1961. During this time they had eaten a lot of dried meat, whereas during the winter they had a more mixed diet. Omitting these subjects the other eight increased by an average of 25%; the four subjects with the highest body activity increased 11% and the four with the lowest values increased 48%. It is probable that the average seasonal variation from autumn to spring for reindeer breeders is between 20 and 50%; for "Lapps, non-reindeer-breeders" and "Lapp children", the increase is about 10 to 20%.

5.2. Change due to new fall-out

Owing to the food-chains involved in this particular human contamination, a rather long delay exists between the entering of the fall-out in the biosphere and its appearance in man. Since the ground during the winter time is covered with snow, the accumulation in lichens is rather limited during this time. Reindeer slaughtered in the winter 1961/62 therefore contained little fall-out from the tests in the autumn of 1961. Most meat consumed during the spring and summer of 1962 came from reindeer slaughtered during the first months of 1962. Therefore it can be assumed that the 1961 fall-out to a rather small extent contributed to the body activity in man until the beginning of the autumn of 1962.

Investigations by SVENSSON and LIDÉN [10] show that the Cs¹³⁷ fall-out during this time increased the specific activity of lichens by about 30 to 40%. About the same increase could be expected to be found in Lapps from April, 1962 to April, 1963. The control group in Jokkmokk (Table VIII)

TABLE VIII

THE CHANGE OF THE Cs¹³⁷ LEVEL IN A CONTROL GROUP
AT JOKKMOKK, SWEDEN, MEASURED IN APRIL, 1962
AND APRIL, 1963

Group	Age (yr)	Sex	Subjects No.	nc/kg		Increase (%)
				1962	1963	
<u>Lapps</u>	11 - 13	M	5	3.15	4.46	42
		F	1	1.64	2.45	49
	14 - 20	M	0	-	-	-
		F	18	2.58	3.10	20
	21 - 40	M	3	7.49	10.46	40
		F	7	3.46	4.06	17
	41 - 65	M	9	6.91	8.75	27
		F	5	4.00	4.75	19
Average			48	4.02	5.06	26
<u>Non-Lapps</u>	33 - 56	M	5	2.88	3.40	18
	42 - 49	F	2	2.85	3.13	10
Average			7	2.87	3.32	16

showed an increase of that order of magnitude. The results from the whole groups from Jokkmokk (1962 and 1963) do not permit a comparison owing to the entirely different sampling methods.

5.3. Activity levels of Lapps and farmers in the whole area investigated in 1963

The results in Table V show a relatively constant Cs¹³⁷ level for the whole area. For the Lapps the highest average values were found in the area (G), where also the maximum body activity of 1360 nc was found. The lowest average value was found in the central part of the whole area (E). From this area comparatively low meat activities have been reported [11], which judging from the interviews, partly could be due to the fact that the supply of grass pasture for reindeer was better here than in other areas.

At all the places studied several male reindeer breeders could not come to the investigation. It can be assumed that they had higher activities than the average obtained for adult Lapps. Values in the 10 nc/kg range are like-

ly to be frequent for them, judging from data obtained for subjects not belonging to the randomly selected groups. The highest rate of absence was found in the areas (A), (B) and (D). The low values found at (A) were therefore probably not really representative for that area.

For non-Lapps (Table VI) the highest values were found at (A). The diet interview also showed that reindeer meat was more frequently consumed here than in the other areas. The highest body activities (490 nc) among non-Lapps were found at (A) and (D).

In Table VII a marked age and sex dependence can be seen. For minors the sex ratio female to male is higher (0.7 to 0.8) than for adults (0.4 to 0.6). The low sex ratio for Lapps in the age range 17 - 20 is probably due to the fact that girls stay longer in school, whereas boys begin reindeer herding with a change in diet towards more consumption of reindeer meat. The age and sex trends are very similar for Lapps and non-Lapps.

6. THE RADIATION DOSE

The annual radiation dose from internally retained Cs^{137} can be calculated by assuming a homogeneous distribution [12]. In the case of the contamination of humans in northern Sweden we have to take into account the annual variation of the body activity. As mentioned earlier, the spring-to-autumn ratio is fairly well under control in the Jokkmokk area. Judging from the diet investigations the annual variation for the other areas is about the same, except for area (A), where the non-Lapp group is more like the Lapp group.

In Tables V and VI the annual radiation dose is given for the groups from different areas. The doses given are calculated by using data due to MIETTINEN *et al.* [3] and assuming a body weight of 70 kg and a height of 170 cm. The doses are calculated for the central value (median) of each area. However, no correction is made for the annual variation of the body activity. Thus, an estimate of the annual dose can be obtained by multiplying the specific activity values given in this paper by eight.

The maximum radiation dose, calculated in this way, for a male Lapp was 151 mrad/a. The corresponding value for a female was 102 mrad/a.

7. PROGNOSIS

From measurements of the fall-out deposition and accumulation rate of Cs^{137} in lichens it is possible to make a rough estimate of the average group body activities to be expected in northern Sweden in the future.

The results of measurements of the specific activity of lichens in 1962 and 1963 [10] indicate that the level of the adult Lapp groups may increase by as much as 40 to 50% from 1963 to 1964. If no further nuclear weapon tests are made, it is nevertheless probable that a substantial but somewhat smaller increase will also occur between 1964 and 1965. After that time a decrease can be anticipated.

On such premises we consider it important to continue the observation of these uniquely high contamination levels of Cs^{137} in human beings.

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HALF-LIFE STUDIES OF RADIOCAESIUM IN HUMANS

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Abstract — Résumé — Аннотация — Resumen

HALF-LIFE STUDIES OF RADIOCAESIUM IN HUMANS. The retention of caesium-137 in humans has been studied in several cases. Two adult men were intravenously administered a small quantity of caesium-137. They were followed about 300 days by frequent whole-body counting and with excreta collection during the initial period. The retention decreased as a sum of two exponentials. The slowest compartment decreased with a half-life of about 75 d.

One of them was also given caesium-137 orally 2 years later with the same excretion pattern obtained as after intravenous injection. The excretion rate of caesium-137 has also been studied in a different way for large groups of men, women and children through comparison with diet data.

From a group of 10 people, voluntarily changing their diet, the average excretion rate could be calculated from whole-body counting at an interval of six weeks. The excretion also has been obtained from a study on two people after an oral administration of caesium-132.

Detailed results on these studies will be given particularly with respect to the elimination rate of caesium, i. e. the biological half-life and its variation with sex and age. On the average, half-lives ranging from 30 to 90 d have been obtained.

ÉTUDES SUR LA PÉRIODE DE RADIOCÉSIIUM CHEZ L'HOMME. La rétention de césium 137 chez l'homme a été étudiée sur plusieurs sujets. Ainsi, on a administré à deux hommes adultes, par voie intraveineuse, une petite quantité de césium 137. On les a suivis pendant 300 j environ en faisant de fréquents dosages de l'activité du corps et en recueillant les excréta au début de la période. La fonction qui représentait la décroissance de la rétention est une somme de deux exponentielles. La fraction qui décroissait le plus lentement avait une période d'environ 75 j.

Deux ans plus tard, on a administré du césium 137 à un des deux sujets, par voie buccale, et on a obtenu le même régime d'élimination qu'après l'injection intraveineuse. On a aussi étudié le taux d'élimination de césium 137 par une méthode différente pour des groupes importants d'hommes, de femmes et d'enfants en faisant des comparaisons avec des données concernant leur régime alimentaire.

Pour un groupe de dix personnes qui avaient volontairement accepté un changement de leur régime alimentaire, on a pu calculer le taux d'élimination moyen en procédant à des dosages de l'activité du corps à des intervalles de six semaines. On a aussi obtenu ce taux pour deux personnes auxquelles on avait administré du césium 132 par voie buccale.

Les auteurs communiquent les résultats détaillés de ces études, notamment en ce qui concerne le taux d'élimination du césium, c'est-à-dire la période biologique et ses variations selon le sexe et l'âge. Dans l'ensemble, on a trouvé des périodes allant de 30 à 90 j.

ИССЛЕДОВАНИЕ ПЕРИОДА ПОЛУВЫВЕДЕНИЯ РАДИОАКТИВНОГО ЦЕЗИЯ У ЛЮДЕЙ. Изучалась задержка цезия-137 у людей при различных обстоятельствах. Двум взрослым мужчинам вводили внутривенно малые количества цезия-137. Пациенты находились под наблюдением 300 дней, в течение которых производились частые измерения радиоактивности всего организма и сбор выделений в начальном периоде. Степень задержки изотопа снижалась как сумма двух экспоненциальных величин. Наиболее медленно изменяющаяся величина снижалась с периодом полувыведения около 75 дней.

Один из пациентов получал цезий-137 внутрь 2 года спустя, причем наблюдался тот же тип выделения, как и после внутривенного введения. Скорость выделения цезия-137 изучалась также другим способом у большой группы мужчин, женщин и детей путем сравнения данных исследования диеты.

При обследовании группы из 10 добровольцев, изменивших свою диету, оказалось возможным рассчитать среднюю скорость выделения на основании измерения радиоактивности

всего организма с интервалом в 6 недель. Выделения определяли также у 2-х человек после приема внутрь цезия-137.

Представлены подробные данные этих исследований, в особенности в отношении скорости выделения цезия, т.е. периода его полувыведения и его вариаций в зависимости от пола и возраста. В среднем были получены сроки полувыведения от 30 до 90 дней.

ESTUDIO SOBRE EL PERÍODO BIOLÓGICO DEL RADIOCESIO EN EL HOMBRE. Se ha estudiado en varios casos la retención de cesio-137 en los seres humanos. A tal efecto, se administró por vía intravenosa una pequeña cantidad de cesio-137 a dos adultos que permanecieron en observación durante unos 300 días, practicándoseles frecuentes exámenes antropogammamétricos, combinados con recogida de excreciones durante el período inicial. La retención disminuyó según la suma de dos funciones exponenciales. El compartimiento más lento decreció con un período biológico de unos 75 d.

Además, a una de las dos personas mencionadas se le administró dos años más tarde cesio-137 por vía oral, siendo la eliminación por excreción análoga a la observada a raíz de la inyección intravenosa. Asimismo, se ha estudiado por un procedimiento diferente (comparación con los valores de la dieta) la velocidad de excreción del cesio-137 en grandes grupos de hombres, mujeres y niños.

Se ha calculado por antropogammametría la velocidad media de excreción, en un intervalo de seis semanas, de un grupo de diez personas que modificaron su dieta voluntariamente. También se ha determinado la velocidad de eliminación por excreción en dos personas a las que se había administrado cesio-132 por vía oral.

Se exponen los resultados detallados de estos estudios, sobre todo en lo que respecta a la velocidad de eliminación del cesio, es decir, al período biológico y a su variación según el sexo y la edad. Por lo general, los períodos biológicos determinados experimentalmente oscilan entre 30 y 90 d.

1. INTRODUCTION

Since 1960 the retention and metabolism of different radionuclides in humans has been studied at our laboratory. These studies have played an important part in our investigation both of various radioactive contamination problems in the biosphere and the use of radionuclides for medical purposes.

One branch of our research programme has been the measurement of retained radiocaesium. The total-body retention has usually been obtained by whole-body counting techniques, but assay of carefully collected samples of the totally excreted urine and faeces has proved valuable, especially in the initial period following administration.

So far only a few results of our metabolic caesium studies have been published, and then very briefly. As more detailed knowledge in this field is desirable, we have made a compilation of our results and present them at this Symposium. For a recent review of other published data, see RUNDO [4].

2. ARTIFICIAL ADMINISTRATION OF RADIOCAESIUM

In September 1960 Cs¹³⁷Cl solution was administered to two male subjects, A and B:1 (a second study of B was performed two years later, B:2; see below) by intravenous injection, preceded by accurate determination of the amount of Cs¹³⁷. Subject A obtained 148 mc and B:1 304 mc. The total-body retention was then determined by whole-body counting in a 42-cm chair arrangement using a 5 in X4 in NaI(Tl) crystal [1]. All excreta were collected during the three days after the administration. At this time the principal purpose of the investigation was the calibration of the chair geometry.

For cases A and B:1 no change of the sensitivity of the counter due to redistribution in the body could be detected after 30 h. The total-body retention was measured frequently during 9 and 12 months for subjects A and B:1 respectively. After 10 d the measured retention could be accurately represented by a one-exponential function for both subjects, corresponding to a biological half-time of 89 and 73 d for A and B:1 respectively.

Detailed analysis of the initial retention pattern was possible by using the results of both excreta assays and whole-body counting. Considerable Cs^{137} excretion was observed during the first few hours after administration compared to the excretion rates found thereafter, and after subtracting the slow excretion component the remaining fast fraction could not be accurately represented by one second exponential only. In adding a third exponential with a biologic half-time of approximately 2 h it was possible to describe the initial phase much better.

Similar results were obtained for two male subjects, C and D, who obtained orally 1240 nc and 1190 nc, respectively, of Cs^{132}Cl solution. These subjects were carefully measured by a whole-body counter, using a scanning bed technique [1,2], which gave accurate results also during the initial period after administration. However, the slow component of the retention curve could not be studied with the same accuracy as in the case of Cs^{137} , owing to the short half-life of Cs^{132} .

In these four cases retention can be described by a sum of three exponentials. The result of the analysis is displayed in Table I, showing the fractions a_1 , a_2 , and a_3 of the administered activity being excreted with rates corresponding to the biologic half-times T_1 , T_2 , and T_3 , which are also given. Although the method of collecting excreta at discrete time points means that the data for analysing the initial period are relatively poor (the first urine sample obtained 3 to 5 h after administration), it is fully evident that a small fraction of the administered activity, 1 to 5%, is eliminated very quickly from the body, corresponding to a biologic half-time of 2 to 3 h. The results obtained so far indicate that a_1 may be larger at intravenous injection than at oral administration; however, further studies are needed in order to exclude a possible effect of biologic variability.

The data plotted in Fig. 1 have been obtained by subtraction of the slow component from the observed total body retention of subject C. This procedure requires a smooth transfer from total-body retention determined by excreta measurement to the same quantity obtained by whole-body counting. The scanning bed geometry is particularly convenient in such a case, owing to its insensitivity to redistribution. The curve shows the retention of the fast components as a percentage of the administered activity. In Fig. 1 the second component is extrapolated and subtracted from the curve, and the obtained difference illustrates the new fast fraction (a_1 , T_1).

In case A the available data are insufficient for a reliable estimate of T_1 and T_2 . Moreover, the varying accuracy ascribed to the data in Table I illustrates the difficulties encountered in analysing excretion data from irregularly-collected samples.

The caesium metabolism of subject B was also studied 2 yr later after an oral intake of 267 nc Cs^{137} as CsCl solution; this case is indicated as B:2. As the first urine sample covered the first 16 h, T_1 could not be determined. We can only say that $T_1 = 2$ to 3 h fits the obtained retention curve,

TABLE I

PARAMETERS OF THE BIOLOGIC RETENTION
OF RADIOCAESIUM OBTAINED ON FIVE MALE HUMAN SUBJECTS
AFTER INTRAVENOUS AND ORAL ADMINISTRATION

Subject	A	B:1	B:2	C	D	E
Age (a)	28	45	47	31	38	28
Weight (kg)	73	74	74	83	88	72
Method	Cs ¹³⁷ i. v.	Cs ¹³⁷ i. v.	Cs ¹³⁷ <u>per os</u>	Cs ¹³² <u>per os</u>	Cs ¹³² <u>per os</u>	Cs ¹³⁷ food intake
Activity (nc)	148	304	267	1240	1190	80
Date of adm.	5/9/60	6/9/60	5/6/62	28/1/63	29/1/63	Jan, 1962
a ₁ (%)	4 ± 1	5 ± 1	1 - 2	2.0 ± 0.5	1 - 2	--- ^{c)}
T ₁ (h)	1.5 - 5	2.0 ± 0.5	--- ^{b)}	2.5 ± 0.5	2 - 3	--- ^{c)}
a ₂ (%)	8 ± 2	9 ± 1	11 ± 1	2.0 ± 0.5	1 - 2	14 ± 3 ^{c)}
T ₂ (d)	--- ^{a)}	1.1 ± 0.2	1.1 ± 0.1	1.5 ± 0.3	0.5 - 1.0	0.7 ± 0.2 ^{c)}
a ₃ (%)	88 ± 2	86 ± 1	87 ± 1	96.0 ± 0.5	96.9 ± 0.5	86 ± 3
T ₃ (d)	89 ± 2	73 ± 2	63 ± 2	72 ± 2	85 ± 7	80 ± 10

Notes: a) Inconsistent data.

b) The procedure of the initial measurements made it impossible to calculate this parameter.

c) The data did not allow a separation of the first two components. The values of a₂ and T₂ include the effect of the first fraction, a₁ and T₁.

an extrapolation of which indicates a value of a₁ of 1 to 2%. The obtained value of T₃, 63 ± 2 d. deviates significantly from that 2 yr earlier, 73 ± 2 d. No explanation of this observation is available. However, the first study was made in the autumn and the second in the summer. It should be mentioned that a temperature effect on the caesium metabolism in mice has been found by FURCHNER and RICHMOND [3], showing an increased excretion rate at lower temperatures.

Subject E (Table I) obtained his Cs¹³⁷ body activity by eating naturally-contaminated reindeer meat (25 nc/kg fresh meat) on seven days out of a period of 16 d. All excreta were collected during this time and also during the following 11 d. Whole-body counting was performed during these periods but only a couple of times during the following two months. Therefore the determination of T₃ and a₃ is less accurate than in the other cases studied, and no separate estimate of the parameters of the two fast components could

TABLE II

URINARY AND FAECAL EXCRETION DATA OF RADIOCAESIUM,
OBTAINED FROM FIVE MALE SUBJECTS*

Subject	Collection period (d)	Excreted activity per day in % of adm. amount		Fraction in faeces, $\frac{F}{U+F}$
		(U)	(F)	
A	0 - 0.8	5.7	-	-
	0 - 2.8	2.9	0.5	0.14
B:1	0 - 1.0	7.4	0.1	0.01
	0 - 3.2	3.4	0.2	0.05
C	0 - 0.9	3.9	-	-
	0 - 3.9	1.7	0.2	0.11
D	0 - 1.0	3.1	0.4	0.12
	0 - 3.0	1.6	0.2	0.14
E	0 - 3 after 1st intake	2.9	0.5	0.14
	0 - 5 after 2nd intake	1.7	0.4	0.19
	0 - 6 after 3rd intake	1.6	0.2	0.13
	0 - 5 after 4th intake	1.5	0.2	0.12
	0 - 12 after last intake	0.6	0.1	0.18

* Cf. TABLE I. U = urine, F = faeces.

be made. In Table I the values of a_2 and T_2 for subject E also include the effect of the first fraction $a_1 - T_1$.

The fraction of radiocaesium excreted in faeces has recently been subject to special interest (RUNDO [4], ROSOFF et al. [5]). In Table II we have collected the data obtained on faecal and urinary excretion in the initial period and, in one case, on a more long-term study. The large amount of radiocaesium excreted on the first day is noticeable. In agreement with

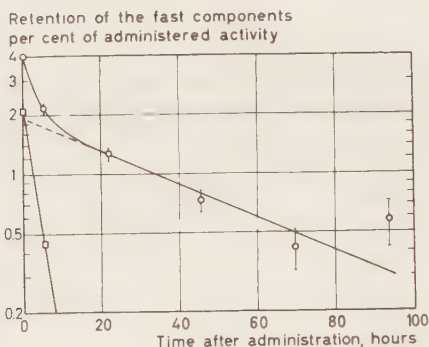


Fig. 1

The biologic retention of the fast components of Cs^{132} in subject C referred to the administered amount of activity. The slow (third) component is mathematically eliminated from the full retention curve. The rest is indicated by circular points and the fraction belonging to the first component by square symbols. The bars indicate 2 S. D.

RUNDO's results the daily faecal excretion in the initial period is 0.2 to 0.4% of the administered activity.

3. CHANGE OF DIETARY INTAKE OF RADIOCAESIUM

In April and May 1962, in connection with our measurements of the enhanced levels of body activity of people in northern Sweden a special study was performed on a group of subjects from the Lapp peoples' high school at Jokkmokk. With 5 males and 4 females, all of them about 20 yr old, and with the 52-yr old male headmaster (H-M) it was agreed that their main sources of Cs^{137} intake, reindeer meat and fresh-water fish, should be omitted from their meals for a period of 5 weeks. They were first measured in our semi-portable whole-body counter [6] at Jokkmokk. On their way back from a two-weeks' trip abroad they were again measured, 36 d later, in the iron room whole-body counter at Lund. All these people (10) showed a pronounced decrease (average 32%) of their initial Cs^{137} level; the latter ranged from 90 to 260 nc. Thus it was possible to obtain a rather good estimate of the average excretion rate with these two measurements. In a control group of 12 subjects from the same school there was a decrease of only 14%.

In Table III the results are summarized. The initial levels have been corrected for intake of Cs^{137} just before the start of the investigation, assuming a value for a_3 of 87%. Except for one subject this correction mounted to less than 1% of the initial body activity.

In this study a certain but small intake of Cs^{137} by normal food (milk, etc.) could appear. A reliable correction for this effect proved impossible. Therefore the measured excretion rate should be a minimum value. Moreover, for one of the boys the biologic half-time became $81 \pm \frac{30}{16}$ d and for one of the girls $97 \pm \frac{17}{7}$ d. If these subjects are omitted, 5 and 10 d shorter average half-time is obtained, as shown in Table III.

TABLE III

BIOLOGIC HALF-TIME (T_3) OBTAINED AS A RESULT OF A TEMPORARILY INTERRUPTED NORMAL DIETARY INTAKE OF Cs^{137}

Subject	Age range (yr)	Weight (kg)	T_3 (d)	2 S. D. (d)
5 males	18 - 25	64	64	8
only 4 males	20 - 25	64	59	6
4 females	19 - 21	53	67	7
only 3 females	19 - 21	55	57	8
H - M (male)	51	58	73	15

These results strongly indicate a half-time of the slow component in the range 50 to 70 d both for 20 yr-old women and men from the actual district of Sweden.

4. BODY BUILD-UP OF Cs^{137} FROM FOOD INTAKE

In a joint study with a Finnish group [7] the present authors had the opportunity to use whole-body counting results together with food consumption data and food activity data in an attempt to calculate average retention rates of Cs^{137} for various groups of Finnish Lapps. Details of this study are given in ref. [7]; in this paper the results only are summarized and set out in Table IV. The age range in the adult groups is large, but most men are 20 to 50 yr old and most women 20 to 60 yr old. The mean age of the boys is 11.5 yr. The short half-time of the latter group is of special

TABLE IV

AVERAGE BIOLOGIC HALF-TIME (T_3) OF FINNISH LAPPS

Group	Number of subjects	Average weight (kg)	Age range (yr)	Average age (yr)	T_3 (d)
Males	50	63	16 - 75	40	64 ± 10
Females	33	57	17 - 76	44	65.5 ± 10
Boys	17	33	10 - 13	11.5	44 ± 10

interest, as it means a faster Cs metabolism in children than in adults. The half-times of the adult group agree well with the data for Swedish Lapps (Table III).

5. THE Cs^{137} METABOLISM IN THE NEWBORN AND THEIR MOTHERS

In our laboratory SVENSSON, BENGTSOON and NAVERSTEN [8] have studied the retention of Cs^{137} and Cs^{132} in mothers and their newborn. The results are summarized in Table V. For comments the reader is referred to [8]. In the present paper we have reported on all studies of radiocaesium metabolism performed in our laboratory to date.

TABLE V

BIOLOGIC HALF-TIME (T_3) OF RADIOCAESIUM IN MOTHERS AND NEWBORN

Subject	Before partus (d)	After partus (d)	Baby (d)
F	33	67 ± 3	21 ± 5
G	--	73 ± 10	--
H	--	32 ± 2	25 ± 3

6. CONCLUSIONS

A diagrammatic representation of all values of T_3 , the slow component, is presented in Fig. 2. From this diagram it is evident that the biologic

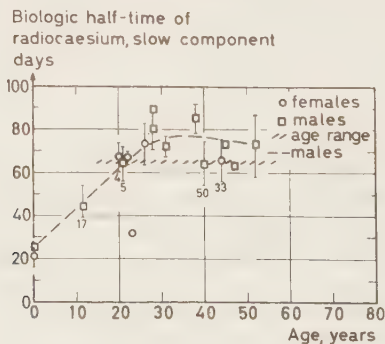


Fig. 2

The biologic half-time (T_3) of radiocaesium, obtained from studies of individuals and groups of people in Sweden and Finland. The number of subjects in a group is given below the plotted average value of the group. The age range (16-76 yr) of group "50" and "33" is indicated in the diagram.

half-time of caesium varies with age. No difference between Lapp groups and other Swedish control persons is observed. From the newborn there seems to be a much faster caesium metabolism; this should be confirmed by further studies. The present material is not useful for an estimate of T_3 older people, but it is very likely that no general increase occurs with age.

The investigations reported above show that a sum of three exponentials describes human caesium retention quite accurately. The first fast component with a biologic half-time of about 2 h has not been reported in the literature before. However, it is well known that a three-component retention function for radiocaesium is valid for several mammalian species [9].

Evidently a rather large biologic variability of the various parameters of caesium metabolism occurs. Therefore further studies of different age groups, at different times of the year, etc., are desirable.

ACKNOWLEDGEMENT

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The Study of ^{57}Co -Vitamin B_{12} -absorption using a Whole-body Counter

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ABSTRACT. A study of the absorption of vitamin B_{12} labelled with ^{57}Co was performed by whole-body counting. The subjects were measured in prone and supine positions by a $\text{NaI}(\text{Tl})$ scintillation detector which moved 150 cm along the subject. The technique was evaluated by model studies, by whole-body counting of subjects and by radioactivity assay of excreta. The influence of body size upon the whole-body counter sensitivity was demonstrated. This influence was considerably diminished when the Compton energy range instead of the photopeak energy range was used for the determination of the radioactivity in the body.

1. Introduction

The absorption of orally administered vitamin B_{12} labelled with radioactive cobalt isotopes may be determined directly by whole-body counting techniques (Heyssel 1966). The procedures are based upon the fact that absorbed B_{12} is eliminated only slowly from the body (biological half-life about one year), while non-absorbed B_{12} is fully excreted by the faeces within about one week. Varying shape and size of human subjects, together with the changing and inhomogeneous distribution of the radioactive material, present problems common to all whole-body counting techniques.

2. Whole-body counter

The low background room (inner dimensions: length 280 cm, width 160 cm, height 190 cm) was built of virgin lead. The floor is 12 cm thick and the roof and the three walls are 8 cm thick. The fourth wall is common with another low background room and is built from laminated iron (total thickness 18 cm), and lined with 3 mm lead (fig. 1).

The whole-body counter consists of two detectors each with a $\text{NaI}(\text{Tl})$ scintillation crystal 12.5 cm in diameter and 10 cm thick, connected to a multi-channel analyser. The detectors are movable in all directions within wide

limits and can be positioned exactly above each other symmetrically on either side of a recumbent patient placed on a specially designed stretcher. The stand system can be motor driven longitudinally on rails at four alternative speeds (5.0, 7.5, 15.0 and 30.0 cm per minute). The stretcher can also be moved laterally by remote control.

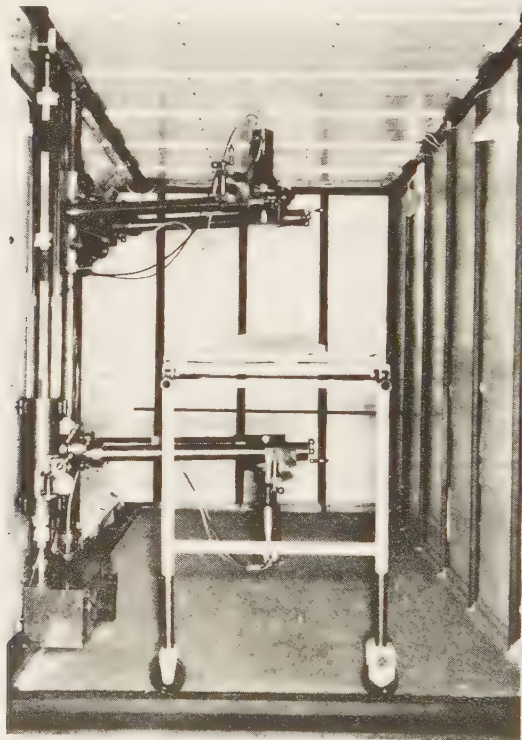


Fig. 1. View of the low background room.

2.1. *Whole-body counting method*

In this investigation whole-body counting was performed by the use of *one detector only*. The distance from the stretcher surface to the surface of the crystal container was 45 cm. Each subject was measured twice, in prone and supine positions (Naversten 1964). Pulses were fed to the multichannel analyser while the detector moved 150 cm at a constant speed from the head of the subject towards the feet. A dead time correction was made by using the mean integral count rate in all the channels of the analyser. The pulse amplitude amplification was adjusted to give 2.5 kev per channel.

3. Calibration of the whole-body counter

^{57}Co disintegrates by electron capture and the principal emission is of energy 122 keV. The spectrum obtained from a point source of ^{57}Co in air 50 cm from the surface of one crystal is shown in fig. 2 (dotted curve). The high energy peak is due to the primary photons of 122 keV and 136 keV emitted by ^{57}Co . The peak on the low energy side is mainly due to the K x-ray photons from excited iodine of the NaI(Tl) crystal. Two pulse height intervals were studied: 43 to 95 keV and 95 to 150 keV corresponding chiefly to the energy range of scattered photons and primary photons, respectively.

Model studies were performed with a point source of ^{57}Co contained in a thin plastic disc. The source was counted in different positions in a non-radioactive phantom of 0.6 cm thick masonite sheets. The total thickness of the masonite model was 21 cm and the average density about 0.9 g cm^{-3} . The results were re-calculated to be valid for a density of 1.0 g cm^{-3} and a model thickness of 19 cm. This estimation was made on the assumption that the vertical geometrical efficiency varied as $h^{-5/4}$, where h was the distance from the point source to a point within the crystal, 5 cm from the front surface (Naversten 1966). A larger source of ^{57}Co in the form of an aqueous solution in a plastic container (dimension: $5 \times 5 \times 10 \text{ cm}^3$) was used to simulate the distribution of the tracer material in the human body after oral administration. It was measured in the same way as the point source with masonite sheets placed above the source to thicknesses of 0, 5, 10 and 15 g cm^{-2} .

From the results of one detector scanning above the phantom, the response of a counting technique, closely simulating that described in section 2.1, was calculated by averaging the mean count-rates of pairs of measurements of the sources placed at the same distance from the upper and the lower surfaces of the phantom ("conjugate mean count-rates", Genna 1966).

4. Measurements of subjects

4.1. Subject groups and tracer material

The absorption of ^{57}Co - B_{12} was studied with the whole-body counter in 6 healthy control subjects (table 1) and 152 patients. Of this latter group, on the basis of several clinical findings, 17 patients were considered to have no disturbance of their B_{12} metabolism and for the present study were regarded as normal (table 2). Data concerning 11 patients with pernicious anaemia are summarized in table 3.

The controls fasted for 4 hours before and for 2 hours after administration of $1.0 \mu\text{g}$ B_{12} labelled with $0.5 \mu\text{Ci}$ ^{57}Co in a gelatine capsule. The patients fasted for 12 hours before and for 2 hours after the administration. The tracer material for the patients consisted of ^{57}Co - B_{12} in 0.1% benzyl alcohol solution, or a freeze-dried preparation (Radiochemical Centre England), or a water solution (Philips Duphar, Holland). To patients numbers 7, 24 and 25 preparations with an activity of $50 \mu\text{Ci}$ ^{57}Co per μg of B_{12} were administered. The other preparations used were between 1 and $3 \mu\text{Ci}$ ^{57}Co per μg of B_{12} .

Table 1. Absorption of $^{57}\text{Co}-\text{B}_{12}$ determined by whole-body counting. Normal male subjects. Dose given: $1\text{ }\mu\text{g B}_{12}$ labelled with $0.5\text{ }\mu\text{Ci }^{57}\text{Co}$.

Subject No.	Age (years)	Serum B_{12} (pg/ml ^[1])	Day of measurement	Retention (%)		Retention (%) corrected to day 14 ^[2]	
				43-95 (kev)	95-150 (kev)	43-95 (kev)	95-150 (kev)
1	35	555	6	60	53	58	51
2	38	470	15	76	78	76	78
3	54	325	8	71	68	69	66
4	27	700	8	50	53	49	51
5	30	570	10	58	57	57	56
6	35	770	7	63	66	61	64
				Mean value: 62		61	
				S.D.: 9		11	

[1] Determined with radio-assay; s.d.=12 pg/ml. (Tibbling 1969).

[2] Measured data corrected to day 14 on the assumption of 3% excretion per week, during the second week.

4.2. Counting procedure

Before administration the radioactivity was measured in a standard geometry using the whole-body counter.

Background measurements (counting time 20-40 minutes) of the patients were performed before administration. After 10-30 minutes the patient was measured again (counting time 10 minutes). Measurements (20-40 minutes) performed 7 and/or 14 days later gave the net retention value. The absorption capacity was expressed as the net retention value as a percentage of the initial value. The whole-body counting method on patients was evaluated in the following ways:

- The effect of redistribution was studied in 9 subjects during the first hours after administration and the reproducibility of the counting method was studied in 6 subjects about one week after administration.
- In 4 patients the absorption of B_{12} was determined by frequent whole-body counting and by accurate radio-assay of carefully collected samples of excreta.
- The retention values obtained by whole-body counting 7 and 14 days after administration were compared in 17 patients considered to be normal.
- The influence of the body weight upon the whole-body counter sensitivity approximately 30 minutes after administration was determined from data of 122 patients.

Table 2. Absorption of ^{57}Co - B_{12} determined by whole-body counting. Patients with no evidence of vitamin B_{12} deficiency

Subject No.	Sex	Age (years)	Serum B_{12} (pg/ml[1])	Administered dose		Retention (%)			
				$\mu\text{Ci } ^{57}\text{Co}$	$\mu\text{g } \text{B}_{12}$	day 7		day 14	
						43-95 kev	95-150 kev	43-95 kev	95-150 kev
7	m	21	386 ± 4	0.6	0.012	70	77	—	75
8	f	81	430 ± 5	0.4	0.4	71	66	69	59
9	f	63	396 ± 8	1.0	1	65	71	63	74
10	m	55	224 ± 10	1.0	1	82	80	80	78
11	f	74	225 ± 5	1.0	1	59	71	—	72
12	m	62	334 ± 6	0.90	0.38	—	—	59	67
13	m	60	178 ± 17	0.72	0.7	39	46	52	52
14	m	57	373 ± 13	0.67	0.7	51	50	39	43
15	f	66	495 ± 25	0.96	1	79	89	50	50
16	m	61	221 ± 14	0.99	0.4	87	99	79	84
17	f	56	352 ± 10	0.89	0.4	86	88	84	98
18	f	60	273 ± 7	0.98	1	57	63	— ^[3]	85
19	f	39	275 ± 13	0.93	0.9	—	—	35	40
20	m	50	520 ± 10	0.95	1	36	37	65	60
21	f	41	553 ± 7	0.88	0.9	52	56	34	34
22	m	46	453 ± 7	0.93	0.9	51	57	51	54
23	f	75	316 ± 21	0.88	0.9	36	37	48	55
Mean value:						61	66	55	63
S.D.:						18	19	16	19

[1] Determined with *Englera gracilis* (Ståhlberg 1967).

[2] The retention of those patients who were not measured on day 14 was assumed to decrease 3% per week.

[3] day 50: 80% by both energy intervals.

Table 3. Absorption of $^{57}\text{Co-B}_{12}$ determined by whole-body counting. Patients with pernicious anaemia

Subject No.	Sex	Age (years)	Serum B_{12} ($\mu\text{g/ml}$)	Administered dose			Retention (%)			
				$\mu\text{Ci } ^{57}\text{Co}$	$\mu\text{g B}_{12}$	Intrinsic factor coli unit	day 7		day 14	
							43-95 kev	95-150 kev	43-95 kev	95-150 kev
24	m	66	$700 \pm 5^{[2]}$	0.38	0.007	—	5	5	4	5
25	f	42	18 ± 1	0.38	0.006	—	15 ^[3]	16 ^[3]	4 ^[3]	5 ^[3]
26	f	73	70 ± 4	0.5	0.5	—	13	14	—	—
27	f	79	52 ± 2	1.0	1	—	—	—	4	4
28	f	64	0	1.06	0.3	—	27 ^[3]	26 ^[3]	7 ^[3]	7 ^[3]
28	"	"	"	0.93	0.2	10,000	72	87	69	81
29	f	73	14 ± 4	0.27	0.1	—	3	2	—	—
29	"	"	"	1.03	0.3	20,000	—	—	64	61
30	m	62	—	0.62	0.6	—	7	9	7	9
31	m	82	$228 \pm 4^{[2]}$	0.94	0.9	—	9	9	—	—
31	"	"	"	0.98	1	10,000	—	—	62	70
32	m	66	4 ± 0	1.06	1.1	—	11	12	—	—
32	"	"	"	0.69	0.7	10,000	61	73	62	76
33	f	62	34 ± 15	0.93	0.9	—	5	6	—	—
33	"	"	"	0.82	0.8	10,000	62	72	— ^[4]	— ^[4]
34	f	65	$336 \pm 16^{[2]}$	0.91	0.9	—	1	2	—	—

[1] Determined with *Evglens gracilis* (Ståhlberg 1967).[2] Treated with vitamin B_{12} before the investigation.

[3] Significant difference between day 7 and day 14. Presumably due to slow intestinal passage.

[4] Day 41: 58% and 69%, respectively.

5. Results

5.1. Results of phantom studies

Fig. 2 shows spectra of the point source placed at different depths in the masonite phantom measured by one detector scanning above the phantom. The count-rate in the high energy region decreased closely following a mono-exponential function with a half value layer of about 5 cm water. When two detectors are used a point source in the middle of a patient, 19 cm thick, would give about 50% as many pulses as a point source at one of the surfaces.

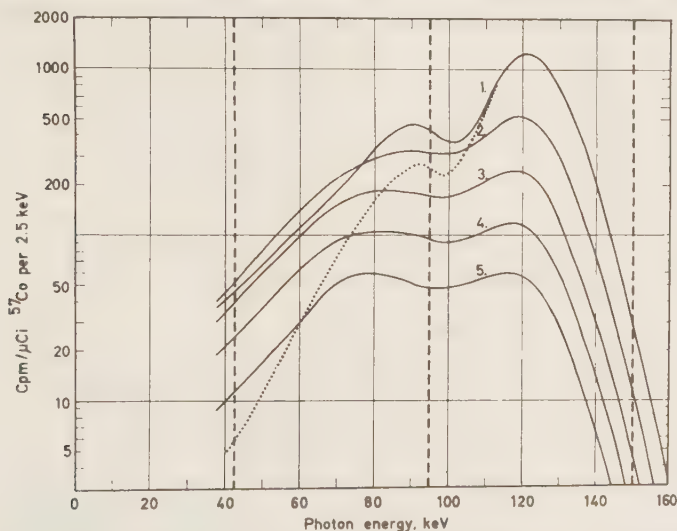


Fig. 2. Pulse height spectrum from a point source of ^{57}Co in air at 50 cm (dotted curve) and at different depths in a masonite phantom. Spectra Nos. 1 through 5 correspond to depths of zero, 4.2, 9.5, 13.8 and 19 cm water, respectively. The pulse height regions, 43 to 95 keV and 95 to 150 keV are indicated by vertical dashed lines.

Because of scatter processes, the mean count-rate in the high-energy region decreases more, with increasing depth, than in the low-energy region. Using the latter region, a two-detector system and normalizing to 100% at the surface of the body, one would obtain about 110% 5 cm below the surface, and about 105% with the source in the middle of the body.

Figs. 3 (a) and 3 (b) illustrate the detector response when the distributed source was placed at different positions in a phantom of masonite, 20 cm thick and of density 1.0 g cm^{-3} . Fig. 3 (a) shows the variation of the response obtained when the phantom was measured with one detector only.

With the high-energy region and a two-detector scan (fig. 3 (b)), there is a variation of about 25% for the source at different depths. If the low-energy region is employed, the response (within the limits of experimental error) is independent of vertical position of the radioactive material. For movements of

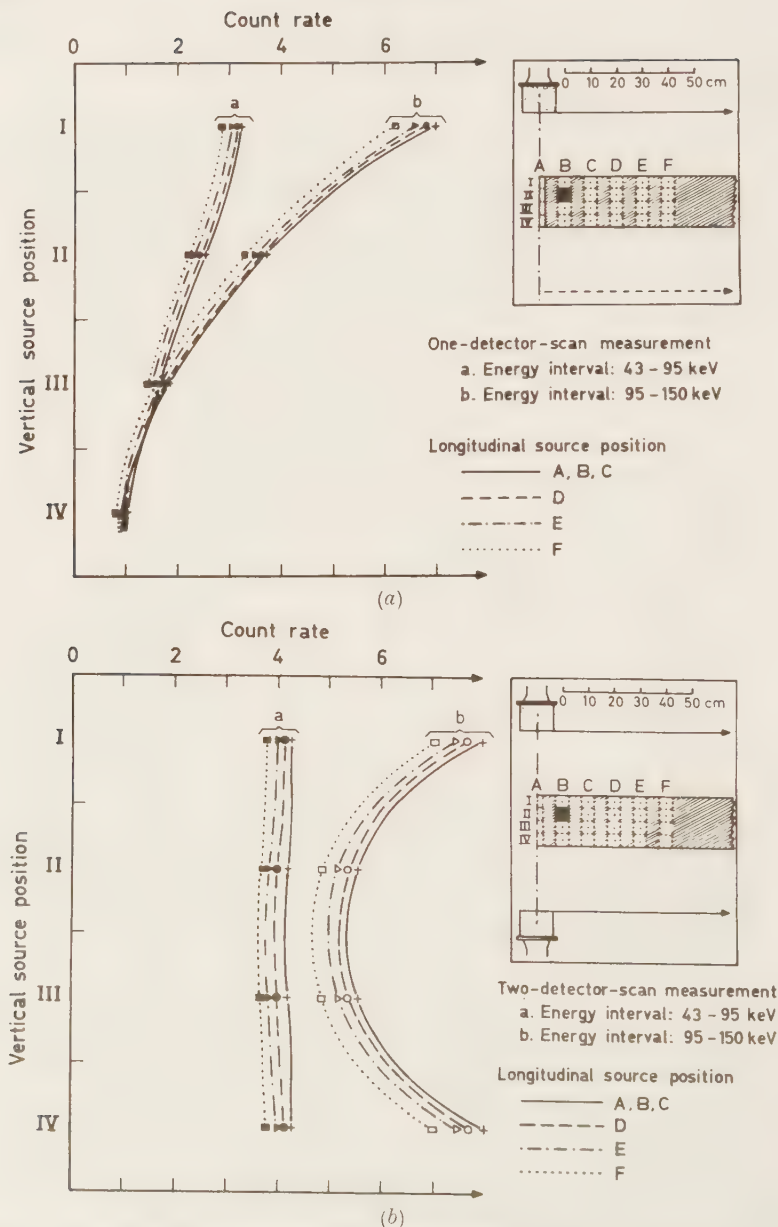


Fig. 3. Count-rate versus position of the distributed source in a water-equivalent masonite phantom. The source was measured at different positions, as indicated. The remaining positions were packed with masonite. The range of vertical source positions is 20 cm and the range of longitudinal source positions is 105 cm. 3 (a) one-detector-scan measurement; 3 (b) two-detector-scan measurement ("the sum of conjugate means")

the radioactive material in the longitudinal direction, the response variation is about 13% if the activity is moved from the middle of the phantom 50 cm towards either end in good agreement with theoretical computations (Naversten 1966).

5.2. Effect of redistribution in human subjects

Comparison of the whole-body counting data and the excreta sample measurements showed some significant deviations which must be caused partly by redistribution of the tracer material. This is clearly shown in fig. 4, where the body retention estimated by a chair geometry (Naversten 1964, 1966) up to day 4 differs from the retention obtained by excreta radio-assay. Similar effects,

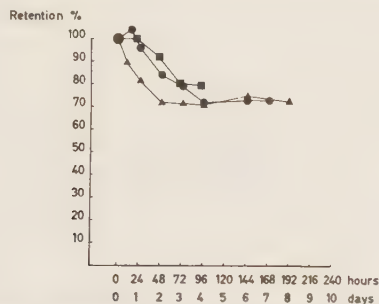


Fig. 4. Retention curves of a normal subject (No. 4) as obtained by:

- ■ ■ excreta measurements;
- ● ● whole-body counting, scanning-bed geometry;
- ▲ ▲ ▲ whole-body counting, chair geometry.

but less pronounced, were observed using the scanning-bed geometry. The same effect was also studied by counting 6 control subjects and 3 patients more than once during the first 3 hours after administration. Table 4 shows the maximum difference relative to the first measurements, in the low-energy region and the high-energy region. Differences of up to 50% in the high-energy region and up to 25% in the low-energy region may occur, particularly in fat subjects. In general, the differences are smaller when the low-energy region is used.

5.3. Reproducibility of counting

The control subjects (table 1) were counted twice to obtain the retention value (day 6 to day 15). The precision, as determined by the difference of paired observations, was 1-2%. In no individual was the difference between the two measurements more than 3 standard deviations of the counting statistics.

The results in 17 subjects with normal serum B_{12} (table 2) may also be used to estimate the counting reproducibility. In patients measured on both day 7 and day 14 the average decrease was 1.4 (S.D.1.8) and 2.4 (S.D.3.4) per cent in the low and the high-energy regions, respectively. As the average retention

Table 4. Effects of redistributions. The difference between a first measurement made before 30 minutes and a second at (2.5 ± 0.5) hours after administration, i.e. before the appearance of any losses through excretion

Subject ^[1] No.	Body weight (kg)	Difference ^[2] %, as obtained from	
		43-95 keV	95-150 keV
1	75	8	17
2	83	29	57
3	69	17	11
4	60	6	0
5	55	12	23
6	77	6	9
Mean value:		13	19
S.D.:		9	20
35	57	15	34
36	58	18	24
37	42	9	11
Mean value:		14	23
S.D.:		5	12
Mean value of 9 subjects:		13	21
S.D.:		7	17

[1] Dose given: Subjects 1 to 6. $1 \mu\text{g}$ B_{12} labelled with $0.5 \mu\text{Ci}$ ^{57}Co in a gelatin capsule.

Subjects 35, 36 and 37. $1 \mu\text{g}$ B_{12} labelled with $0.5 \mu\text{Ci}$ ^{57}Co in a solution with 0.1% benzyl alcohol (Radiochemical Centre, England).

[2] The difference is expressed as a percentage with reference to the first measurement.

was about 60% , these figures correspond to a weekly "decrease" of (2 ± 3) and $(4 \pm 5)\%$. The results indicate (1) that normally very small amounts of administered B_{12} remain unabsorbed on the 7th day; and (2) that the precision of the counting method, including patient positioning and counting statistics, is about 2% .

5.4. Comparison of the scattered photon region with the full energy photon region

In most cases (c.f. tables 1, 2, 3) the percentage retention value in the high-energy region (PRV_H) was higher than the corresponding value in the low-energy region (PRV_L). The average value of the ratio $(\text{PRV}_H - \text{PRV}_L)/\text{PRV}_L$ was 10% . In a group of 38 subjects with 6 healthy persons (table 1) and 17 patients with normal serum B_{12} (table 2), the difference could not be correlated with body weight or with the retention value. It is assumed that the activity is situated at different depths in the body at the time of the initial and the final retention measurements since the liver is more superficially situated than the gastro-intestinal tract. The initial value will therefore be too low and consequently the PRV_H too high.

5.5. Body weight dependence

Data from the measurements of 122 patients were analysed in order to estimate the whole-body counter sensitivity (S = count rate per $\mu\text{Ci } ^{57}\text{Co}$). Fig. 5 shows the sensitivity plotted against body weight, w (kg), of the patient.

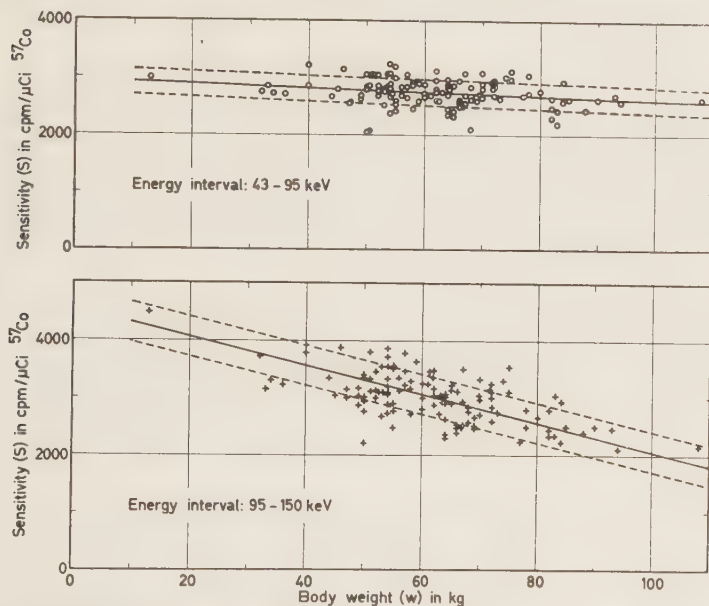


Fig. 5. Pooled data of 122 patients showing the sensitivity (as obtained within 30 minutes after oral administration) correlated to the body weight. The data were analysed by the method of least squares. The dashed lines indicate one standard deviation.

The data were analysed by the method of least squares. The equation for the line of best fit for the low-energy region is

$$S_L = 2.95 \cdot 10^3 - 3.3 w$$

and for the high-energy region,

$$S_H = 4.56 \cdot 10^3 - 25 w.$$

The sensitivity values S_L and S_H vary by 1% and 9% per 10 kg body weight, respectively. The standard deviation for a single patient (weight 70 kg), as indicated by the dashed parallel lines, is 8% and 12%, respectively. The wide spread of the individual observations indicates the existence of factors not directly correlated to the body weight such as body shape and varying tracer mobility in the gastro-intestinal tract. The data in this section as well as the previous data confirm that the best results will be obtained by using the low-energy region.

5.6. Clinical results

In table 1 data on 6 healthy men are presented. The retention values were obtained after 6 to 15 days. The percentage retention was corrected to day 14 assuming a daily excretion of 0.5% (section 5.3.) The average retention on day 14 estimated by the lower energy region was 62% (S.D. = 9%) and by the higher energy region, 61% (S.D. = 11%).

In table 2 the same data are given for patients assumed to be "B₁₂-normal". In close agreement with data in table 1 the percentage retention on day 14 was 59% and 63% obtained in low and high-energy regions. However, the spread was wider here (standard deviations: 17 and 19%, respectively). In all individual results in tables 1 and 2 the counting statistics error is about 1.5%, that is, of the order of one unit in the percentage retention. The small number of subjects does not allow an analysis of the relation of the retention to age, sex, or to serum B₁₂ values.

Table 3 shows the data of 11 patients with verified pernicious anaemia. Without "intrinsic factor" the mean retention for the group was about 6% (S.D. = 4%). Thus, there seems to be little risk of overlapping of the range of the values of normal subjects and of patients with pernicious anaemia. Furthermore, when the radioactive B₁₂ was given with "intrinsic factor" (patients number 28, 29, 31, 32, 33) the retention was raised to between 50 and 80%.

6. Conclusion

Whole-body activity measurements using a dual detector scanning method substantially reduce the effects of distribution of activity for radionuclides emitting 120 keV γ -rays. The pulses caused by scattering photons rather than those of primary photons should be used for whole-body counting. This allows the body activity of ⁵⁷Co to be determined with an accuracy of about 10%. The minimum detectable activity in a 40 minute measurement is about 0.002 μ Ci ⁵⁷Co. In routine examinations, where counting times should not exceed 10 minutes, a suitable administered dose would be about 0.1 μ Ci ⁵⁷Co, which results in a radiation dose to the liver of less than 20 mrad.

RÉSUMÉ

L'étude de l'absorption de la vitamine B₁₂ marquée avec ⁵⁷Co au moyen d'un compteur de l'activité du corps entier

L'étude de l'absorption de la vitamine B₁₂ marquée avec ⁵⁷Co a été faite au moyen de comptage du corps entier. Les personnes mesurées étaient couchées sur le dos et sur le ventre, et on se servait d'un détecteur à scintillations au NaI(Tl), qu'on mouvait 150 cm le long du corps de la personne. La technique était évaluée par des études de modèles, par comptage du corps entier de personnes et par l'analyse radioactive des excréments. On a démontré l'influence de la grandeur du corps sur la sensibilité du compteur de l'activité du corps entier. Cette influence était considérablement réduite quand on employait une gamme d'énergie Compton au lieu de la gamme d'énergie du pic photo-électrique pour déterminer la radioactivité dans le corps.

ZUSAMMENFASSUNG

Untersuchung der Absorption von mit ⁵⁷Co markiertem Vitamin B₁₂ mit Hilfe eines Ganzkörperzählers

Die Absorption des mit ⁵⁷Co markierten Vitamins B₁₂ wurde mit Hilfe der Ganzkörperzählung studiert. Die untersuchten Personen wurden (indem sie auf dem Rücken oder auf dem Abdomen

lagen) mit einem NaI(Tl) -Szintillationsdetektor gemessen, welcher 150 cm entlang dem Körper der Person bewegt wurde. Dieses Verfahren ist durch Modelluntersuchungen, Ganzkörperzählung der Subjekte und radioaktive Analyse der Exkremente ausgewertet worden. Es wurde der Einfluss der Körpergrösse auf die Empfindlichkeit des Ganzkörperzählers gezeigt. Dieser Einfluss wurde erheblich verringert, wenn, anstatt des Photospitzen-Energiebereichs, der Compton-Energiebereich für die Bestimmung der Radioaktivität im Körper verwendet wurde.

Резюме

Исследование поглощения витамина B_{12} , меченого ^{57}Co , при помощи счетчика для измерения активности всего тела

Поглощение витамина B_{12} меченого ^{57}Co исследовалось при помощи счета активности всего тела. Субъекты подвергались измерению, лежа ничком и навзничь, при помощи сцинтилляционного детектора NaI(Tl) , который передвигали на расстоянии 150 см вдоль тела субъекта. Эта техника подвергалась оценке модельными исследованиями, счетом активности всего тела субъектов и радиоактивным анализом испражнений. Показано влияние величины тела на чувствительность счетчика для измерения активности всего тела. Это влияние значительно уменьшалось, когда вместо области энергии фотолинии применялась область энергии Комптона для определения радиоактивности тела.

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A STUDY OF TOTAL BODY POTASSIUM DETERMINATION
USING A WHOLE-BODY COUNTER

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SUMMARY

Total body potassium determination for clinical uses is studied using a scanning-bed whole-body counter with two NaI(Tl) scintillation detectors. For the calibration an IN VIVO dilution technique with K-42 is used. It is shown that the present counting method effectively minimizes effects of redistribution and body shape. For routine uses the $(W/H)^{1/2}$ calibration curve is suggested instead of the use of the more complicated individual K-42 calibration.

1. INTRODUCTION

Potassium is important for vital processes in animals, such as biocatalysis, muscular contraction and propagation of nerve pulses, etc. In vertebrates, it is mainly found inside living cells (MANERY 1954). A small fraction also occurs extracellularly. In man, total body potassium is almost proportional to the lean body mass (= body mass minus bone mineral, fat and water). About 70 mmol K per kg lean body mass is usually found (FORBES et al. 1961, ANDERSON and LANGHAM 1961). This means that healthy young adult men and women typically contain about 150 g K and 100 g K, respectively.

From each gram of naturally occurring potassium, an average of 3.35 photons with the energy 1.46 MeV are emitted per second from its long-lived isotope K-40, isotope abundance 0.012 % and $T = 1.3 \times 10^9$ a. It is therefore possible to assess the body content by simply counting these photons.

Methods for whole-body potassium determination with external counting techniques are of great potential importance in medicine. The reason for this is that other methods (chemical analysis on plasma or tissue samples, kinetic studies, K-42 dilution techniques, skin-fold thickness, etc.) are tedious, time-consuming and inaccurate when such results must be extrapolated to a measure of the total body potassium content and cell mass.

External counting techniques can have responses that vary with the internal activity distribution of the human body, as well as with the body stature, from patient to patient. For accurate and precise potassium determinations, it is important that those variations are kept as low as possible and that the counting system has a high sensitivity.

The whole-body counting techniques have to be calibrated. Since there exist no other IN-VIVO methods of adequate precision, the calibration has to be done with a special dilution technique involving administration of K-42 to humans, as well as to a potassium standard phantom, followed by accurate comparison of corresponding count-rates of K-42 and K-40.

Our group in Lund has earlier reported on thorough methodological studies of different counting geometries and different radionuclides (CEDERQUIST and LIDÉN 1962, CEDERQUIST 1964, NAVERSTEN et al. 1969). In this particular study, the calibration and some count variation performances are analysed with special reference to total body potassium determinations.

It is concluded that the present scanning whole-body counting technique may intrinsically have a high degree of accuracy for total body potassium determinations, but a long counting time is needed for an adequate counting precision.

2. METHODS

2.1. Whole-Body Counting Method.

The whole-body counter, shown in Figure 1, consisted of a low-background room with a patient bed and a detector-stand (NAVER-STEN et al. 1969). Two NaI(Tl) scintillation detectors, diameter: 12.5 cm, thickness: 10 cm, were adjusted one above and one below the patient so that the axes of the cylinders were coinciding. The detectors were motor-driven with constant speeds along the

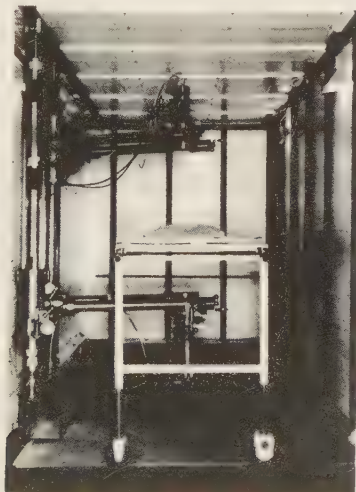


Figure 1. Low-background room with counting detector system and patient bed.

patient's body by a remote controller. A mixed pulse amplitude spectrum of counted photons in both detectors during the whole scanning time were stored in the memory of a multichannel analyser (Inter-technique SA40B).

The following counting parameters were chosen because of the requirements of high counting efficiency and maintaining an adequate low dependence on the body stature of adult persons, even with extreme over-weight (cf. Figure 2):

- * Scanning length: 150 cm
- * Distance between the detector faces: 50 cm
- * Distance from the upper detector face to the upper surface of the patient bed: 35 cm
- * Start position of scanning: nose-eye level

2.2. Method of Calibration.

The calibration was performed through accurate comparisons of the count-rates of K-40 and K-42 in human subjects and a standard of natural potassium. In principle, it was based on the similarity of the photon energies, 1.46 MeV and 1.52 MeV, respectively, as emitted from these isotopes. It could be assumed that the effects of photon absorption and scattering in the subject and in the scintillation detector were identical, if adequate correction was made for the use of the spectral pulse distribution due to the photon energy difference.

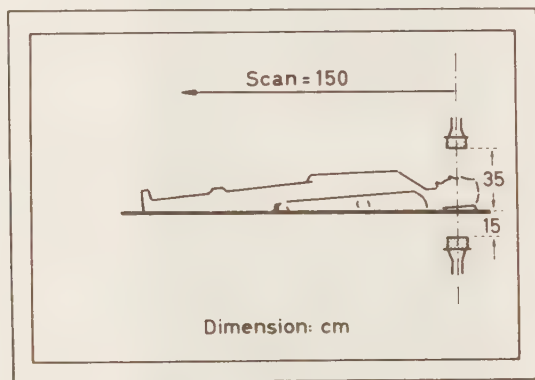


Figure 2. Schematic representation of counting geometry.

By this method (as used by Burch and Spiers, 1953, and MILLER and MARINELLI, 1956), the counting efficiency of K-40 in a human subject related to that of K-40 in a standard would be the same as the counting efficiency of K-42 in the same human subject related to K-42 in the same standard, i.e:

$$\frac{S-40(\text{man})}{S-40(\text{standard})} = \frac{S-42(\text{man})}{S-42(\text{standard})} \quad \dots\dots(1)$$

where S-40 and S-42 were count-rates per unit mass ($\text{s}^{-1} \text{g}^{-1}$) of potassium and per unit source strength ($\text{s}^{-1} \text{Bq}^{-1}$) of K-42, respectively. If R-40 was the measured count-rate due to the total body mass of potassium, m-40, then

$$S-40(\text{man}) = \frac{R-40(\text{man})}{m-40(\text{man})} \quad \dots\dots(2)$$

From EQUATION 1 we could then get the following expression for the measured total body potassium in man.

$$m-40(\text{man}) = R-40(\text{man}) * \frac{1}{S-42(\text{man})} * \frac{1}{S-40(\text{standard})} \dots\dots(3)$$

$$S-42(\text{standard})$$

EQUATION 3 could also be written as:

$$m(K) = \frac{c}{f(W,H)*s} \dots\dots(4)$$

where m(K) = mass, (g), of body potassium in the subject.

c = in a prescribed interval of the pulse spectrum of the measured net count-rate (s^{-1}) of K-40 in the subject.

s = in the same interval of the pulse spectrum of the measured net count-rate of K-40 per gram ($s^{-1} g^{-1}$) of potassium in the standard.

f = f(W,H) = factor relating the counting efficiency in individual subjects to that of the standard. The factor was assumed to be dependent on the weight, W, and on the height, H, of the subject.

2.3. The Potassium Standard.

A cuvette, made of polyacrylate was used as a laboratory reference standard of potassium. Outer dimensions: 38.0 cm * 30.0 cm * 2.5 cm. Inner dimensions: 35.0 cm * 27.6 cm * 1.9 cm. It contained 292 g K as KCl (Merck AG, PRO ANALYSIS) in 1830 ml of water solution.

Identical cuvettes were used for the measurement of the pulse amplitude distribution of K-40 or K-42. The activity of K-42 was injected, in about 0.5 ml, into the water solution, followed by careful mixing. The cuvette was then placed in a phantom of masonite sheets, 5 mm thick, built in the shape of an elliptical cylinder (length 50 cm, major diameter 30 cm and minor diameter 16 cm). The purpose of this phantom was to obtain similar energy distributions of the photons from man and from the potassium standard.

The validity of EQUATION 1 was dependent on identical, though separate, counting geometries of K-40 and K-42 in the subject and in the standard. This meant that the geometry and procedures of the subject and the standard could be optimized rather freely. Furthermore, according to EQUATION 1, it did not require a detailed knowledge of the decay scheme of K-40 and K-42. The calibration method should give a quantitative result if decay correction of K-42

($T_{1/2} = 12.36$ h) was made, and if the potassium content of the standard was known by another method.

The standard was counted with the same scanning procedure as was used for man, but it was placed on the bed exactly at the middle of the scan.

2.4. Pulse Energy Ranges.

In whole-body counting with NaI(Tl) scintillation detectors, the net content of the full energy peak of the pulse amplitude distribution usually has been used as a measure of the body activity. In this study, three energy ranges were evaluated (Table 1). ENERGY RANGE 1 principally contained the full energy peak and was chosen so as to minimize possible effects of small electrical drifts. The ENERGY RANGES 2 and 3 were selected particularly to study the change of the counting performance when scattered photons were included. The lower cut-off of RANGE 3 at 540 keV was chosen above the background peak at 511 keV and the lower cut-off of RANGE 2 to exclude potential problems of Cs-137 ($h\nu = 0.662$ MeV) in subjects, and also to eliminate varying background due to Bi-214 ($h\nu = 0.609$ MeV), a dominant gamma-emitter descendent of atmospheric Rn-222.

Table 1

	K-40	K-42
Energy range 1	1300 - 1560 keV	1360 - 1620 keV
Energy range 2	800 - 1560 keV	800 - 1620 keV
Energy range 3	540 - 1560 keV	540 - 1620 keV

2.5. Human Subject Groups.

As mentioned above, the counting accuracy could be dependent on to what degree efficiency variations can be related to anatomical parameters, such as weight and height. The influence of different potassium distributions was therefore studied in three ways after i.v. injection of K-42 in physiological 0.9 % sodium chloride solution:

- * by repeated profile recordings with a slit collimator on a subject until 23 hours after injection of K-42 (Figure 3)
- * by repeated whole-body counting on a subject after injections of K-42 twice (Figure 4)
- * by a calibration procedure on a group of subjects after injection of K-42 (Figure 5)

All the counting data were corrected to reference time for the physical decay of K-42, as well as for urine excretion. No

fecal excretion occurred during the studies.

3. RESULTS

Examples of profile recordings after scanning along the human subject with a 4 cm slit lead collimator, 5 cm thick, are shown in Figure 3. Ordinate values indicate the net count-rate of K-42 at different parts of the body after i.v. injection of 0.7 MBq K-42.

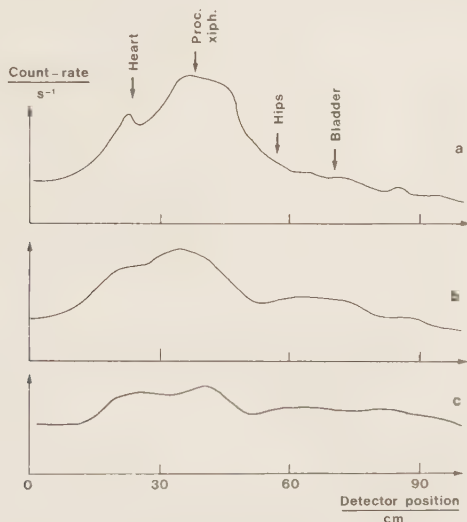


Figure 3. Profile diagrams after i.v. injection of K-42.

Start of scan a) at 2 minutes

b) at 40 minutes

c) at 22.5 hours

Arrows show the approximate location of the heart, distal end of sternum, anterior superior iliacal notch and bladder. Each profile was performed in about 4 minutes.

Figure 4 shows the relative counting efficiency of K-42 after i.v. injection of 0.02 to 0.04 MBq of K-42 on two occasions on the same subject as in Figure 3. Data points indicate all the individual measurements, in the first study until about 24 hours, and in the second study until about 46 hours after injection. Results in Figures 3 and 4 are based solely on the use of ENERGY RANGE 1.

Relative counting response

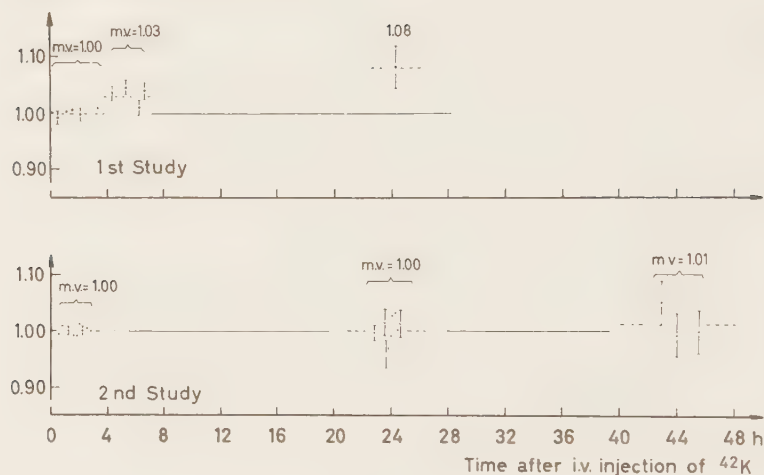


Figure 4. Time-dependence of relative counting efficiency after two repeated injections of K-42 (the same subject as in Figure 3). Bars indicate counting uncertainty by one S.D.

Figure 5 shows, at the left hand ordinate, the efficiency factor, and at the right hand ordinate, the sensitivity. Both are related to the index of body thickness as obtained from a group of volunteers. The measurements were evaluated for three energy ranges (Figures 5a,b,c). The regression lines calculated by the least-square method are indicated. The dependence of the energy range is illustrated in Figure 5d, together with the uncertainty of the lines indicated by one standard error. The squares indicate a trice repeated study of an obese subject during a banting period of two weeks, while the body weight decreased from 102.8 kg to 98.2 kg. In this case, only the data from the first study was used in the regression analysis.

Quantitative data of the regression analysis for $(W/H)^{1/2}$, W/H , W and H as independent variables are given in Table 2. Here 14 subjects were counted during the first hour as well as at one day after injection, while nine subjects were only counted within the first hour. In order to reveal any systematical difference, numerical analysis was therefore performed separately on those groups.

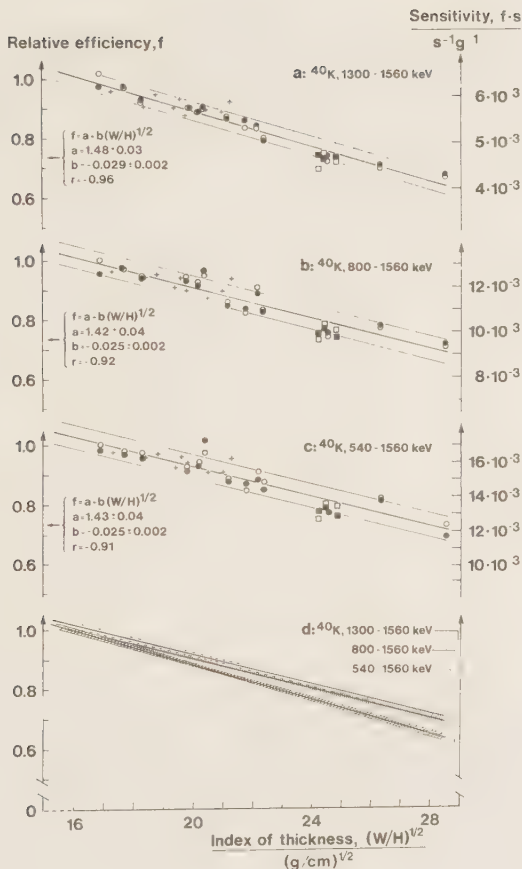


Figure 5. The efficiency factor, f , and the sensitivity, $f \cdot s$, related to the index of body thickness, $(W/H)^{1/2}$. Open circles (o) and squares (◻) indicate subjects counted during the first hour. Filled symbols, (●) and (■), are subjects counted at about 24 hours after injection. Cross marks (+) show subjects counted only during the first hour. See also TABLE 2. Squares represent a triple study of a subject during banting.

In order to evaluate the total precision of the K-42 calibration methods according to EQUATION 3, as well as the above obtained $f(W,H)$ -method, one subject ($W = 76,5$ kg, $H = 174,5$ cm) participated with administration of K-42 four times at one-week intervals. Table 3 shows the measured masses of body potassium obtained from ENERGY RANGES 1 and 2. Average f -factors in comparison with those from the regression line are also given.

TABLE 2a.

Relative efficiency, $f = a + b(W/H)^{1/2}$, studied with linear regression analysis by the method of least squares using data from K-42 calibration on three groups: 14 subjects counted at 0.5 h (A) and 24 h (C), and 9 subjects counted only at 0.5 h (B).

Group:Energy range	Intercept	Slope	Correlation coefficient
	a $\pm$ 1S.D.	b $\pm$ 1S.D.	r
A:1	1.52 $\pm$ 0.05	-(31.2 $\pm$ 2.4)10 ⁻³	-0.97
A:2	1.46 $\pm$ 0.07	-(26.9 $\pm$ 3.2)10 ⁻³	-0.93
A:3	1.43 $\pm$ 0.07	-(25.0 $\pm$ 3.2)10 ⁻³	-0.91
B:1	1.15 $\pm$ 0.13	-(12.0 $\pm$ 6.7)10 ⁻³	-0.56
B:2	1.22 $\pm$ 0.14	-(14.8 $\pm$ 7.1)10 ⁻³	-0.62
B:3	1.20 $\pm$ 0.11	-(12.8 $\pm$ 5.7)10 ⁻³	-0.65
C:1	1.45 $\pm$ 0.04	-(27.7 $\pm$ 1.6)10 ⁻³	-0.98
C:2	1.39 $\pm$ 0.06	-(24.0 $\pm$ 2.9)10 ⁻³	-0.92
C:3	1.43 $\pm$ 0.07	-(25.1 $\pm$ 3.3)10 ⁻³	-0.91
A+B:1	1.50 $\pm$ 0.05	-(30.3 $\pm$ 2.2)10 ⁻³	-0.95
A+B:2	1.43 $\pm$ 0.05	-(25.9 $\pm$ 2.5)10 ⁻³	-0.92
A+B:3	1.42 $\pm$ 0.05	-(24.5 $\pm$ 2.4)10 ⁻³	-0.91
A+B+C:1	1.48 $\pm$ 0.03	-(29.2 $\pm$ 1.4)10 ⁻³	-0.96
A+B+C:2	1.42 $\pm$ 0.04	-(25.1 $\pm$ 1.8)10 ⁻³	-0.92
A+B+C:3	1.43 $\pm$ 0.04	-(24.9 $\pm$ 1.9)10 ⁻³	-0.91

TABLE 2b

Correlation coefficient for $f(W/H)$ against $(W/H)^{1/2}$, W/H , W and H after linear regression analysis by the least squares method as in TABLE 2a.

Group:Energy range	$(W/H)^{1/2}$	W/H	W	H
A:1	-0.97	-0.95	-0.94	-0.25
A:2	-0.93	-0.91	-0.90	-0.16
A:3	-0.91	-0.90	-0.88	-0.11
B:1	-0.56	-0.55	-0.47	-0.06
B:2	-0.62	-0.61	-0.53	-0.13
B:3	-0.65	-0.64	-0.55	-0.12
C:1	-0.98	-0.85	-0.97	-0.28
C:2	-0.92	-0.77	-0.90	-0.17
C:3	-0.91	-0.79	-0.90	-0.13
A+B:1	-0.95	-0.94	-0.93	-0.06
A+B:2	-0.92	-0.91	-0.89	-0.02
A+B:3	-0.91	-0.91	-0.87	+0.06
A+B+C:1	-0.96	-0.89	-0.89	-0.13
A+B+C:2	-0.92	-0.84	-0.89	-0.06
A+B+C:3	-0.91	-0.85	-0.89	-0.02

TABLE 3

Total body potassium determinations (g K) on the same subject during 23 days, calculated by the K-42 standard method according to EQUATION 3, and by the regression line method according to EQUATION 4. The $\bar{f}$ -values are the means of f obtained by each method.

W = 76.5 kg

H = 174.5 cm $(W/H)^{1/2} = 20.9 \text{ (g/cm)}^{1/2}$

K-42 method

$(W/H)^{1/2}$ -method

	Energy range 1	Energy range 2	Energy range 1	Energy range 2
1st Study	138	134	133	128
2nd Study	129	137	138	133
3rd Study	136	137	139	132
4th Study	145	137	144	134
Average	137	136	139	132
(Max-min)/2	8	2	6	3
$\bar{f}$	0.91	0.86	0.87	0.90

4. DISCUSSION

4.1. Geometry and Attenuation.

As has been shown earlier, (NAVERSTEN 1966) the counting efficiency of the whole-body counter depends both on the geometry of the human subject in the counter and on the photon absorption and scattering in the body. The profile study as reported here demonstrates in Figure 3 that there actually is a significant redistribution within the body during the first 6 hours after i.v. injection, while it thereafter until 23 hours is less clearly seen with this method. The results indicate a fast turn-over in agreement with published data (GOLDMAN, YALOW, GROSSMAN and GARELICK 1963). They report that potassium initially after injection is trapped in different organs in proportion to their share of the cardiac out-put. For instance, in the first minutes about 20 % of administered activity can be found in the kidneys. In our study, we also see an early redistribution from the heart and the regions of liver, spleen and kidneys, indicating that an equilibrium state is approached during the first 24 hours. The magnitude of the K-42 redistribution demonstrated could have a significant effect on the whole-body counting results, especially during the first hours after administration. This was also drastically demonstrated by MILLER and MARINELLI 1956 with the Marinelli-chair geometry. However, we made two repeated studies on a subject for the special purpose of evaluating this effect. Until two days after injection we could not see any significant change in the response of our counting technique (Figure 4). The analysis of the data on 23 persons (from the groups of Table 2) did not show significant change in sensitivity from 0.5 h to 24 h after injection either. These results show that the scanning geometry is effective for evening out counting effects of uneven activity distribution.

The correlation of counting efficiency to the body stature is particularly studied on a group of volunteers. As reported here in Figure 5 and Table 2, there is a significant correlation to parameters of weight and height.

Theoretically, there are two major parameters that effect the degree of correlation to weight and height, namely the counting geometry and the photon attenuation in the body. In the first case it could be assumed to be a dependence proportional to $(WH)^{1/2}$, i.e. a rough approximation of the solid angle under which the detector "sees" the human subject. For photon attenuation, it is related to an exponential coefficient proportional to "effective body thickness". Again, using the same simplified assumptions, $(W/H)^{1/2}$ could be regarded as an "index of thickness". Therefore a formula $f = f(W, H)$ could be assumed, as in EQUATION 5. MENEELY et al., 1962, used a similar concept for a Marinelli-chair geometry technique.

$$f = \text{const} * (WH)^{-1/2} * e^{-\text{const} * (W/H)^{1/2}} \quad \text{.....(5)}$$

where "const" is two different constants. As the dependence of $(WH)^{1/2}$ and $(W/H)^{1/2}$ is small, the formula can be written as

$$f = a' * [1 - b'(WH)^{1/2}] * [1 - c'(W/H)^{1/2}] \quad \text{.....(6)}$$

where a' , b' and c' are positive constants.

It can be seen from EQUATION 6 that a complicated dependence with terms of a 'linear' dimension, $(W/H)^{1/2}$, a 'square' dimension, $(WH)^{1/2}$, and a 'volumetric' dimension, W , can be assumed. However, from earlier investigations (NAVERSTEN 1966), it is known that, with the scanning technique, the dependence of geometry is less pronounced than that of attenuation effects. Since it in any case is a slow dependence, we have chosen as our main hypothesis to correlate f to the index of body thickness. Then

$$f = a + b * (W/H)^{1/2} \quad \text{.....(7)}$$

Since EQUATION 7 has been deduced through successive approximations, and in order to evaluate the validity of the hypothesis, we have chosen to correlate f also to W/H , W and H , according to the following formulas:

$$f = a + b * (W/H) \quad \text{.....(8)}$$

$$f = a + b * W \quad \text{.....(9)}$$

$$f = a + b * H \quad \text{.....(10)}$$

where a 's and b 's are different constants in Equations 7, 8, 9 and 10.

In Table 2 it is seen that there are strong correlations to $(W/H)^{1/2}$, W/H and W , while H is almost without correlation to the counting efficiency. This result confirms earlier findings that variations due to attenuation are the dominant parameter, while the effect of longitudinal geometry is less pronounced (NAVERSTEN 1966). It is confirmed that $f(W,H)$ is best correlated to $(W/H)^{1/2}$ which indicates that an average posterior-anterior diameter would be a better parameter than body weight. Comparing the different energy ranges, the strongest correlation is found when the full energy peak is used. The lower slopes for Ranges 2 and 3 show that scattering processes of photons play an important role in diminishing the variation with body stature. For a complete compensation, however, an even wider energy range with cut-off below 500 keV has to be used.

4.2. Precision and Accuracy.

The errors in the body potassium determinations are mainly due to the spread in data caused by

- * electronic instabilities
- * background instabilities
- * statistical counting precision

In addition, systematical errors can be introduced mainly by errors in the mass of potassium in the standard and errors in the physical decay time of K-42. These errors together are estimated to be less than 2 %.

ELECTRONICAL INSTABILITY mainly causes drift of the energy pulse amplification of the multi-channel analyser, including the high voltage of the detector. This drift was studied with careful spectral measurements of a point source of Na-22 (photon energies: 0.511 MeV and 1.275 MeV). It showed a day-to-day precision at 1.5 MeV to be of the order of 5 keV (1 S.D.). For the ENERGY RANGES 1, 2 and 3, this would introduce an uncertainty of 1.2 g K, 0.6 g K and 0.6 g K, respectively. The main contribution came from an error in the background count-rate, while the uncertainty had rather little influence on the counting sensitivity.

The BACKGROUND COUNT-RATE was specially investigated. Table 4 shows the spread of data in 44 background determinations during about one month. Besides a variation due to counting statistics and electrical instability, there is also a contribution that could be due to variations of the atmospherical radon-daughter concentration.

The STATISTICAL COUNTING PRECISION has independent contributions in a series of steps in the K-42-method of the potassium determination. The spread contribution (1 S.D.) in the efficiency factor in this investigation was about 3 % and the spread of the data points correlated to $(W/H)^{1/2}$ gave an estimated standard deviation from the regression line of about 3.5 % for subjects of normal weight, but about 5 % for highly obese subjects. The spread of data points may thus be due to counting statistics as well as due to bodily conditions.

TABLE 4

The precision of background count-rate.
The counting precision is defined as $1 \text{ S.D.} = N^{1/2} / t$,
where N is the number of registered counts in the time, t;
t = 60 minutes. The experimental precision of 44
determinations in one month is defined by 1S.D., where

$$1 \text{ S.D.} = \left(\frac{\sum (x_i - \bar{x})^2}{N - 1} \right)^{1/2}$$

	Energy range 1	Energy range 2	Energy range 3
Background ($\bar{s}^{-1}$)	1.13	4.35	7.05
Counting precision ($\bar{s}^{-1}$)	0.013	0.033	0.045
Experimental precision ($\bar{s}^{-1}$)	0.018	0.043	0.060

Based on the present data and judging from the standard error of f, (c.f. Figure 5d) together with the above mentioned systematic error of the potassium standard, we should have an error of less than 3 % in the calibration factor obtained from the regression line.

In addition to this, there is a statistical uncertainty in the K-40 counts of each patient. In Table 5, the magnitude is presented for a typical male (150 g K) subject and a typical female (100 g K) subject. Sixty minutes counting time is assumed for both patient and background. The precision obtainable with 1000 minutes background count is given in parenthesis. It shows that if the laboratory can keep a high degree of electronic and ventilatory stability, it is possible to improve this part of the counting precision from 5 g K to below 4 g K.

The OVER-ALL UNCERTAINTY of the potassium determination was evaluated by four entirely repeated K-42 calibration procedures on one subject according to EQUATION 3 in ENERGY RANGES 1 and 2. From this the mean relative counting efficiency, f, was determined, with a counting precision of 4%, corresponding to a standard error of about 2% in f. As is seen in TABLE 3, the measured $\bar{f}$ and the calculated $\bar{f}$ agreed within +/-4%. Since the data in TABLE 3 were independent of the data in Table 2, we could say that the magnitude of the errors of both methods is the same. The precision of the $(W/H)^{1/2}$ -method could, however, be significantly enhanced with a larger group of calibration subjects. The total spread of data confirms that for the $(W/H)^{1/2}$ -method the largest part of the spread is from the K-40 counting of the patient himself. The non-consistent spread of the points of the trice repeated study of the obese subject also is partly explained in this way. The regression line method in routine is therefore a good substitute for the much more complicated K-42 calibration study for total body potassium determination of individual patients.

TABLE 5

Counting precision of the net count-rate of K-40 in man, calculated on 100 g K and 150 g K, roughly corresponding adult women and men, respectively. Assumed subject counting time was 60 minutes and background counting time was 60 minutes. The precision with 1000 minutes background counting time is given in parenthesis.

		Energy range 1	Energy range 2	Energy range 3
Background (s^{-1})		1.13	4.35	7.05
Sensitivity($s^{-1} g^{-1}$)		$5.5 \cdot 10^{-3}$	$11.7 \cdot 10^{-3}$	$15.0 \cdot 10^{-3}$

100 g K				
S.D.	(%)	5.0(3.9)	4.5(3.4)	4.4(3.3)
S.D.	(g K)	5.0(3.9)	4.5(3.4)	4.4(3.3)

150 g K				
S.D.	(%)	3.6(2.8)	3.3(2.4)	3.0(2.3)
S.D.	(g K)	5.3(4.2)	4.9(3.6)	4.5(3.4)

6.CONCLUSION

The method of total body potassium determination with a scanning whole-body counting technique is seen to be suitable for clinical studies of different diseases. This study confirms that the technique very effectively minimizes effects due to redistributions of radioactivity within the body and due to body shape. $(W/H)^{1/2}$ is the best parameter of body shape with the counting geometry used.

With the apparatus used here, the body potassium in independent 60-minute measurements can be assessed at the 95 % confidence level within about 12 g K for average-sized women and men. Excluding systematic errors, the limit is about 10 g K. Improvements in this figure for the apparatus that has been used can primarily be obtained with a longer counting time of the patient, i.e. repeated counting performances. Alternatively, the counter should be equipped with a larger detector volume.

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